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Feasibility and Environmental Implications of Using Waste Motor Oil as Alternative Supplemental Fuel in Contingency Prime Power Generation

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FEASIBILITY AND ENVIRONMENTAL IMPLICATIONS OF USING WASTE MOTOR OIL AS ALTERNATIVE SUPPLEMENTAL FUEL IN CONTINGENCY PRIME POWER GENERATION

THESIS

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DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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FEASIBILITY AND ENVIRONMENTAL IMPLICATIONS OF USING WASTE MOTOR OIL AS ALTERNATIVE SUPPLEMENTAL FUEL IN CONTINGENCY PRIME POWER GENERATION

THESIS

Presented to the Faculty

Department of Systems Engineering and Management

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In Partial Fulfillment of the Requirements for the

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Abstract

In an era of strict hazardous material-handling restrictions and intense energy savings projects, the Department of Defense has an opportunity to take advantage of a waste-to-energy initiative by looking to vintage diesel engine technology for inspiration. The idea comes in the form of recycled waste motor oil which can be used as a fuel in compression-ignition engines. When mixed at a low blend ratio, waste motor oil can supplement diesel fuels to extend the range of fuel stores for electrical power generating equipment at contingency military bases while simultaneously decreasing the burden on fuel supply chain management and the hazardous waste disposal stream

This research looked at the feasibility of filtering, and then burning waste motor oil blends. It also explored potential drawbacks which can threaten the lifespan of modern diesel engine components. Analytical methods included spectrometry, chromatography, viscometry, electron microscopy, and Gaussian dispersion modeling to study filtering method effectiveness, engine component wear, and air pollution effects.

The waste motor oil was diluted with diesel fuel to a point where metal concentrations were reduced to trace amounts. This dilution allowed engine exhaust emission levels to remain below permissible exposure levels without the assistance of engine emissions mitigation hardware. The Department of Defense can use these results for decisions-making when balancing energy security and environmental implications.

Acknowledgments

I would like to thank my family and friends for encouraging me to complete this endeavor and putting up with my demanding schedule. I could not be more thankful to be located so close to home during this rough but rewarding tour. Of course, I can’t forget the staff at the 88th Medical Group who helped me overcome some trying events during my tour here.

I received immense support from the 88th Air Base Wing here at Wright-Patterson AFB. The Civil Engineer Group and Logistics Readiness Squadron procured test samples for this research while enduring my painstakingly detailed data requests. Along with the local help I received, I must pay my gratitude to the countless Power Pro and Water/Fuels System Maintenance Airmen I have met throughout my career so far. I have gained invaluable knowledge as they took me on site visits and taught me about their crafts.

Thanks to my thesis committee for pushing me in the right direction throughout this research. I want to give special thanks to Dr. Dan Felker for helping me overcome a steep learning curve in analytical chemistry, while conducting multiple laboratory experiments.

In regards to technical support with diesel engine systems and fuels, the teams at CEMIRT, BEAR Acquisitions, ALS Tribology, Fryer-to-Fuel, and Cummins all provided valued input. I received immense help from Mr. Cliff Burbrink, a fuels chemist at Cummins and my high school chemistry and physics teacher who developed my foundation that spurred me on with a passion for science and engineering.

Finally, I would also like to thank many friends I have met in the M35A2 “deuce-and-a-half” restoration hobby. We have held many interesting debates about fuel blending, all for the good of the hobby. I came to AFIT with a passion for learning more about alternative fuels and I only hope to carry that forward into my next tour with BEAR Base at Holloman AFB.

Z Bierhaus

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FEASIBILITY AND ENVIRONMENTAL IMPLICATIONS OF USING WASTE MOTOR OILS AS AN ALTERNATIVE SUPPLEMENTAL FUEL IN CONTINGENCY PRIME POWER GENERATION

I. Introduction

General Issue

In the final days of World War II, a problem arose when General George Patton's 3rd Army exceeded expectations on the march to Germany. Gen. Patton's jeeps, trucks, and tanks outran his fuel supply, and all the usable German petroleum depots had been previously targeted and destroyed by Allied aerial bombing (Patton, 1947). The United States War Department realized that it was a massive undertaking to fuel a marching army. During WWII, 55% of the tonnage shipped overseas was fuel. During the Korean war, this rose to 67% (Blackburne & Sawyer, 1960).

After WWII, the U.S. Army conducted research to address this problem. The military's complex and arduous logistic requirement to deliver fuel to the combat theater sparked an interest in developing an engine that could operate on a wide range of low-cost fuels (Shipinski, Myers, & Uyehara, 1967). By collaborating with U.S. agricultural tractor engine manufacturers and utilizing post-war German combustion research, the Army developed the "multifuel" engine.

Interest in multifuel capabilities stems primarily from the logistic requirement of the military or the desire of the user to utilize low-cost fuels but was also an emergency capability in the event a military unit needed to get out of a situation where no primary fuel was available. The compression-ignition concept engine was designed to burn primarily diesel fuel, but the components of the engine were built robustly to handle a wide array of similar fuels – incorporating almost any combustible fuel a marching army could get its hands on in a combat zone. These permissible fuels included jet fuel, kerosene, gasoline, commercial burner oils, etc. They are detailed later in Table 4 which is copied from Army Technical Manual 9-2320-361-10 (U.S. Army, 2006).

Increasingly over the past decade, civilian collectors have been buying retired multifuel-powered vehicles such as the classic Vietnam era 2-1/2-ton and 5-ton cargo trucks from government surplus auctions. To fuel these trucks affordably, private owners have experimented with fuels outside the scope of the Army's permissible fuel listing, to include Waste Vegetable Oil (WVO) and Waste Motor Oil (WMO). Both are readily available to the public and usually free of charge to anyone willing to haul them away. With various levels of filtering to ensure removal of harmful impurities, many fuel blends have been created and discussed in hobby sectors of the general public.

The precision manufacturing and fuel injection technology of today has increased fuel efficiency and power output, while decreasing the harmful exhaust emissions from compression-ignition engines using state-of-the-art common rail fuel supply and various other refined hardware and computer software components. But this increased performance comes at a price. The ability to consume multiple fuel sources, such as WMO blends, may be hampered by more sensitive fuel systems and environmental regulations.

When thinking of multiple fuel sources, the spectrum broadens to any refined petroleum product. There is an abundance of used petroleum products in deployed military bases produced by ground vehicle and aircraft maintenance shops. One subject of this research is the disposal of these products within the hazardous waste stream. If it is legal and feasible to collect these products before disposal and/or recycling, the research will continue into the practicality of processing the products for use as fuel in the DoD's War Reserve Materiel (WRM) modern electrical power generators.

As found by Capt Daniel Amack in his 2014 thesis, *Waste-to-Energy Decision Support Method for Forward Deployed Forces,* waste-to-energy projects have the capability to offset the security risks associated with convoy operations and reduce the reliance on the fuel. They add a measure of self-sufficiency to their daily operation, no longer being as reliant on a supply of fuel being sent to their location (Amack, 2014).

Rationale

Goals of the Department of Defense include reducing energy consumption (EPAct 05), greenhouse emissions (EO 13693), and the costs of fuel purchase and transport. This research aligns with those goals by looking at ways to reduce the burden on the hazardous waste stream while finding a suitable substitute for WMO recycling. Waste-to-energy recycling offers an advantageous solution to this situation. The concept is to utilize existing filtration and storage systems to render the WMO as a usable fuel for deployed location diesel power generation while taking air pollution factors into consideration. The final goal of this research, if proven feasible, will be to develop possible operating procedures for Air Force Civil Engineer craftsmen to collect and filter WMO for use as an alternative supplementary fuel for power plants at deployed locations.

At the present time, fuel is relatively inexpensive. However, it fluctuates and may be expensive yet again. More burdened cost is incurred when the military must haul it in to combat zones either by aircraft, naval vessel, or truck which can cost servicemen and women their lives. A 2009 Army Environmental Policy Institute study showed that in 2007 alone, one soldier was killed or wounded for every 35 fuel resupply convoys in Iraq and Afghanistan. That was 170 casualties over 6030 convoys to transport 589,841,670 gallons of fuel in one year (AEPI, 2009) A 2010 Noblis report for the Strategic Environmental Research and Development Program titled *Sustainable Forward Operating Bases* found that at the peak of Operations Enduring Freedom and Iraqi Freedom in 2007, DoD operations in Iraq and Afghanistan were consuming 22 gallons of fuel per soldier per day. This was a 175% increase since the Vietnam War. By 2008, DoD was consuming over two million gallons of fuel per day (Noblis, 2010).

At Wright-Patterson AFB in FY15, the entire base used six million gallons of fuel, represented in Figure 1. 92% of that was Jet-A used in aircraft. The remaining 8% was for ground vehicles and generators. 4% was gasoline, either regular unleaded or E85 ethanol. The remaining 4%, or 244,000 gallons was diesel fuel, either D1 winter blend, D2 summer blend, or B20 biodiesel. Since the base does not rely on generating its own electricity, almost all the diesel fuel was used to fuel ground vehicles.

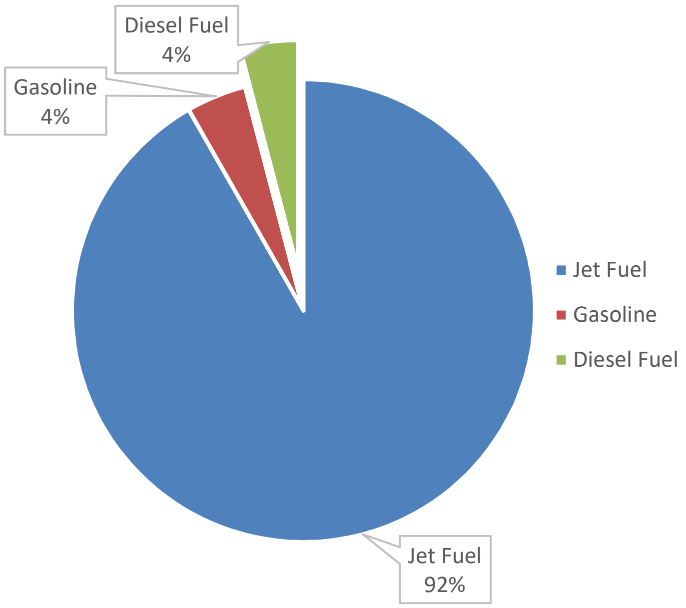


Figure 1 - FY15 Fuel Usage at Wright-Patterson AFB

In addition to this fuel usage information, the 88th Civil Engineer Squadron's Environmental Flight reported that Wright-Patterson AFB disposed of approximately 39,000 gallons of WMO in CY16. Relating the amount of oil disposed to the amount of total fuel consumed by the base gives 39,000 gallons of oil to 6,000,000 gallons of fuel, or 0.65%. This number does mean much, but puts the ratio into perspective.

Nonetheless, it was reported by the Air Force Petroleum Agency (an office within Defense Logistics Agency) that in CY16, Al Dhafra Air Base used 1.6 million gallons of diesel fuel just to generate electricity (Defense Logistics Agency, 2017). Making a bold assumption, if Al Dhafra disposes of approximately the same amount of WMO as Wright-Patterson AFB does in a year, then the potential blend percentage of available WMO to diesel fuel used in generators could be 39,000 gallons of oil to 1,600,000 gallons of fuel, or 2.4%. This number will be significant in later discussion and will compare to a manufacturer's allowable blend ratio.

All this WMO is considered hazardous waste, however, according to 40 CFR § 279.1, as soon as it is mixed with a fuel to be used as a fuel, then it is no longer subject to used oil regulations, which will be explained in the chapter II (EPA, 2012). For the purposes of this study, WMO will be limited to SAE 5W-30 and 15W-40 conventional motor oils and Automatic Transmission Fluid (ATF). Realistically however, WMO will cover a range of automotive and aircraft fluids to include motor oils, transmission fluids, brake fluids, hydraulic fluids, and even dirty diesel and gasoline emptied from spent fuel filter cartridges. They are collected in one common point called a satellite accumulation area, as can be seen in Figures 2 and 3. These fluids can all be mixed together, filtered, and used as a substitute for diesel fuel.

Figure 2 - Waste Motor Oil Collection Area with Filter Crusher

Figure 3 - WMO Satellite Accumulation Area

This study examines the feasibility of burning these byproducts as a fuel supplement. It may not be a simple yes or no but instead may define a threshold of certain WMO components that a generator engine can handle. All blends of these fluids are known to produce less power and more harmful emissions than regular diesel, but the extent is not well known. This study will primarily address the physical and chemical characteristics of these blends to compare them to diesel fuel but will also investigate the potential for harmful exhaust emissions and potential damage that could affect a modern generator's fuel delivery system.

Current Events

The researcher held a phone interview in July 2016 with Mr. Patrick Ross, the powered support systems foreman for the Civil Engineer Maintenance Inspection and Repair Team (CEMIRT). Located at Tyndall AFB, Florida, CEMIRT is responsible for keeping a portion of the USAF's complex WRM assets in excellent working condition. This team is comprised of individuals each with decades of experience in the field of electrical power production equipment.

In early July 2016, a hot topic in the news was the dramatic and unexpected event of a military coup in the country of Turkey. Following this event, all electrical power and supplies to US military installations were cut off, which triggered the continuous use of backup emergency power for six days. The power production team at Incirlik Air Base ran 156 emergency generators and two prime power plants for 24 hours a day until local grid power was restored. As the political turmoil lingered, the bases quickly depleted their diesel fuel reserves. The deployed engineers at these bases called back to CEMIRT for expedient technical assistance. They needed to know what different types of fuels their generators could burn and what repercussions, if any, would result from operating on alternative fuels. The team at Tyndall quickly discovered that this task was not straightforward as they found that there were seventeen manufacturers of generators being used across the bases in Turkey at the time. The specifications of each engine needed to be analyzed before a final answer could be given. CEMIRT worked tirelessly to determine what kinds of alternate fuels their generators could burn and to what percent of blending would ensure adequate fuel system lubrication. In addition, when operating on alternative fuels, power output de-rating had to be calculated to determine the capability of each generator set. This proved to be a daunting task, but resulted in all military bases gaining a posture for energy security in the event that diesel fuel did indeed run out. (P. Ross, phone interview, 28 July 2016)

Research Questions

The Air Force has an opportunity to revive an old concept for waste-to-energy recycling for combat applications. After review of an engine manufacturer's recommendation, it was determined that it is feasible to burn oil in a modern diesel engine fuel delivery system, which will be further discussed in the next section. There are limitations with supplementing diesel fuel with alternative blends, but the following research questions should address whether this idea is feasible and how it effects the environment:

- How much filtration is required for WMO to be considered clean enough for use?
- What harmful environmental effects exist?

Research Focus

For electric power generation at deployed locations, Air Force Civil Engineers employ a wide variety of generator sizes available in the Basic Expeditionary Airfield Resources (BEAR) kit. While the intent of this research is to identify a fuel blend that will have minimal issues in any diesel generator, the answer is not straightforward. Each engine manufacturer has its own set of design specifications to which they build. If this research were to attempt to find a blanket fuel blend that applies equally to all generators, it would have implications on ability to collect a broad spectrum of data.

Wide ranges of specifications vary with engine manufacturer, size, use, and local emissions regulations, causing the researcher to limit the focus of this topic and choose one engine to target all technical considerations. The researcher chose the largest engine in the Air Force WRM fleet, the Cummins QSK38. The engine powers the Air Force's 800kW BEAR Power Unit (BPU) in contingency locations around the world. The BPU is shown in Figure 4.

The engine in the obsolete MEP-012a generators (replaced by the BPU) was based on a marine application, the KTA38-G7. It was a 1080-horsepower prime power unit which utilized Cummins' patented Pressure-Time (PT) mechanical fuel injection system. This system was very robust and already compatible with JP-8, a kerosene based aircraft engine fuel with almost unnoticeably different characteristics to diesel fuel (Drake, 2010). The BPU uses this same base engine platform, but upgrades include moving to an electronic fuel injection system, the Modular Common Rail System (MCRS) which is more sensitive to particles in the fuel. An Air Force contract modification remedied this by specifying a different set of injectors that allow for multifuel operation utilizing primarily diesel and JP-8. The injectors are manufactured by Bosch. This retrofitted model of engine became the QSK38-G5 (Cummins, 2009). Cummins has declared in its fuel specifications, that a blend of oil may be used to enhance diesel fuel lubrication properties, but the maximum recommended blend ratio is 5% oil to 95% diesel fuel. Recall earlier in this chapter that it was estimated that Al Dhafra Air Base only produced enough WMO to make a 2.4% blend ratio. From this point forward, Cummins' 5% blend will be addressed. Anything less will be considered allowable as seen fit with any other recommendations.

Figure 4 - BEAR 800kW Power Unit with Cummins QSK38

Methodology

The methods used in this research will include filtration, chromatography, and microscopy performed at the AFIT laboratory paired with titration, viscometry, spectrometry, and other services rendered by a contracted tribology lab. All methods will be discussed in Chapter III. Analytical test results were compared to OSHA exposure limits and a Cummins, Inc. fuel service bulletin.

Assumptions and Limitations

This research assumes the reader has limited but sufficient prior knowledge on the matter of diesel fuel, electrical power generation, the nature of supply and logistics in a combat environment, and a moderate to advanced chemistry and physics background. Testing methods, chemical properties of motor oil, and advanced components of a diesel engine will be explained in detail.

Due to limited resources, time, and challenges with local lab equipment, many tests were contracted to a tribology lab. The limitation with the most impact was the inability to carry out a particle measurement and concentration test. This information was crucial to determining the effect on an engine's fuel delivery system components. Without this, the researcher made several assumptions and consulted experts in the field of alternative diesel fuels.

Implications

Obtaining a test engine would have also been beneficial, but the 5% oil blend cap set the threshold for testing relatively low to begin with. Testing oil blends in an engine would not have given fidelity of test results without hundreds of hours of running and would have required highly detailed analyses of components after use. This is a destructive test method, meaning the engine components likely would have been run to failure in the name of research and would have cost the government more money than necessary in repair bills.

One commonly discussed property is the cetane number which relates to the ignition quality of diesel fuel. It is expected that cetane number will have minimal impact from adding oil to fuel. This educated suspicion combined with the fact that a very expensive standard engine would need to have been attained to carry out the physical characteristics test led to the decision to leave the subject out of the discussion.

Definition of Terms

Waste Motor Oil or Used Oil is a byproduct from performing maintenance on equipment. It is defined by 40 CFR § 279 *Standards for the Management of Used Oil* as any oil that has been refined from crude oil, or any synthetic oil, that has been used and as a result of such is contaminated by physical or chemical impurities (*Code of Federal Regulations*, title 40, sec. 279.1)

Disposer is used in this thesis as "generator" to distinguish between the meaning of electrical power generating equipment and the EPA-defined definition as follows; A disposer means any person, by site, whose act or process produces used oil or whose act first causes used oil to become subject to regulation.

Collector, or transporter, means any person who transports used oil, any person who collects used oil from more than one generator and transports the collected oil, and owners and operators of used oil transfer facilities.

Processing means chemical or physical operations designed to produce from used oil, or to make used oil more amenable for production of, fuel oils, lubricants, or other used oil-derivative product. Processing includes but is not limited to: blending with virgin petroleum products, blending used oils to meet fuel specification, filtration, simple distillation, chemical or physical separation, and refining.

Preview

In a contingency environment where lives are on the line, electrical power must be uninterruptable and energy must come from a secure source. Environmental concerns must be at the forefront of daily operations but may be a lower priority when security is the main concern. Having alternative fuels in mind is never a bad idea when it comes to the defense of the nation.

Conclusion

This research will look at mid-twentieth century U.S. Army research, as well as newly rediscovered interest from the civilian hobby sector for technical support. This WMO recycling idea has been attempted before, but emissions regulations have hampered the effort. With the advent of more refined emissions control hardware, this idea may yet again gain traction.

II. Literature Review

Introduction

The World Environment Conference held in Kyoto in 1997 confirmed the drastic need to reduce petroleum waste discharge into the environment (Leask, 1998). In fact, it was estimated that less than 45% of available waste oil was being collected world-wide in 1995. The remaining 55% was either misused or discarded by the end user in the environment. In this sense, the treatment and reuse of oils provides a suitable way for WMO management by promoting energy conservation and environmental sustainability.

For example, 1 liter of waste oil re-processed as fuel contains about 8000 kilojoules of energy, or 2.2 kilowatt-hours, which is enough energy to light a 100-Watt bulb for nearly 1 day (El-Fadel & Khoury, 2001). According to the 88th Civil Engineer Group's Environmental Flight, in 2016, Wright-Patterson AFB disposed of 39,374 gallons (149,047 liters) of WMO. By the same extrapolation, Wright-Patterson could have provided 1,192,344,000 kilojoules, or 331 Megawatt-hours which could power the entire base for one day.

As explained by a 2009 Government Accounting Office report to the Subcommittee on Readiness, Committee on Armed Services in the House of Representatives, the DoD reported for the fiscal year 2007, that it had consumed almost 4.8 billion gallons of mobility fuel which cost $9.5 billion to taxpayers. This cost represents less than three percent of the DoD's total budget – the DoD has estimated that for every $10 increase in the price of a barrel of oil, operating costs increase by approximately $1.3 billion (Solis, 2009). Three percent may seem insignificant, but considering the massive magnitude of the DoD's budget, it is a significant burden on the American taxpayer. Any methods of energy conservation that do not compromise mission safety need to be considered.

Disposal of WMO

Each year, the U.S. generates about 1.4 billion gallons of used oil. There are approximately 700,000 facilities that qualify as disposers including a wide range of businesses that use automotive lubricants in addition to industrial, hydraulic, metalworking and other oils (Arner, 1995).

As defined by the Resource Conservation and Recovery Act (RCRA) of 1976 and Hazardous and Solid Waste Amendments of 1984, there are three players in the oil recycling business: generators, collectors, and processors (Bell et al., 2011). For the purposes of this research to eliminate confusion with the term "generator" as it is used to describe electrical power generation machinery, from this point forward, a person or place generating waste oil will be known as a "disposer". Disposers are the mechanics doing maintenance on equipment. These mechanics are draining the fluids to be disposed. Collectors are the middlemen that purchase and transport the WMO in trucks to collection facilities. Processors employ different methods of recycling or disposal depending on their local market and environmental regulations. Not all collectors are processors, but in most cases, it makes good business sense for the processor to own his own truck for collection from his customers. In the case of this research, the DoD will perform all three roles. On a military installation, the motorpool and aircraft maintenance hangars are the generators, either the aircraft and vehicle maintainers or civil engineers are the collectors, and power production and water/fuels maintenance craftsmen are the processors.

The EPA's Resource Conservation and Recovery Act (RCRA) has some leniency on the issue of burning WMO for energy recovery. As stated in 40 CFR § 279.11, used oil may be burned for energy recovery as long as it meets a few specifications. Those are listed below in Table 1 (EPA, 2012).

Table 1 - Used Oil Specifications (EPA, 2012)

Constituent/Property	Allowable Level
Arsenic	5 ppm maximum.
Cadmium	2 ppm maximum.
Chromium	10 ppm maximum.
Lead	100 ppm maximum.
Flash Point	100°F minimum.
Total Halogens	4,000 ppm maximum.

In addition to RCRA leniency, a DoD agency even recommends WMO blending. According to the Joint Service Pollution Prevention Opportunity Handbook, it is possible to recycle used lubricating oils generated from fluid changeouts. On-site recycling options for used lubricating oil are typically limited to energy recovery such as diesel fuel supplementation. The criteria that must be used in electing on-site recycling options involve the volume of use lubricating oil generated annually. Diesel fuel on-site use includes the volume of diesel fuel used, volume of lubricating oil generated, diesel engine warranty, and activity policy. Recycling of used oil may allow the used oil to fall under the less stringent regulations of 40 CFR § 279 as opposed to the hazardous waste regulations in 40 CFR § 260-268. In addition, under 40 CFR § 261.5, generators who recycle their used oil and manage it under 40 CFR § 279 do not have to count the used oil in their monthly totals of hazardous waste generated. The decrease in the quantity of hazardous waste generated monthly may help a facility reduce their generator status and lessen the degree of regulatory requirements (i.e. recordkeeping, reporting, inspections, transportation, accumulation time, emergency prevention and preparedness, emergency response) applicable under RCRA, 40 CFR § 262. Recycling used oil on site generally requires a facility to store large quantities of used oil. Development and implementation of a Spill Prevention, Control, and Countermeasure Plan is required under 40 CFR § 112 for facilities that store certain amounts of oil on site. In addition, the burning of used oil on site may require an air permit (JSPPOH, 2000).

Finally, to understand what types of oil are being recycled, a representative sample based on real world application must be modeled. Since this mixture changes day to day depending on the type of maintenance scheduled in the vehicle shop and the barrels are filled up on approximately a weekly to monthly basis, a fixed recurring mixture is impracticable to capture. To compensate for this, a mechanic at the 88LRS large vehicle maintenance shop provided his experienced estimate on WMO fluids collection ratio, shown in Figure 5.

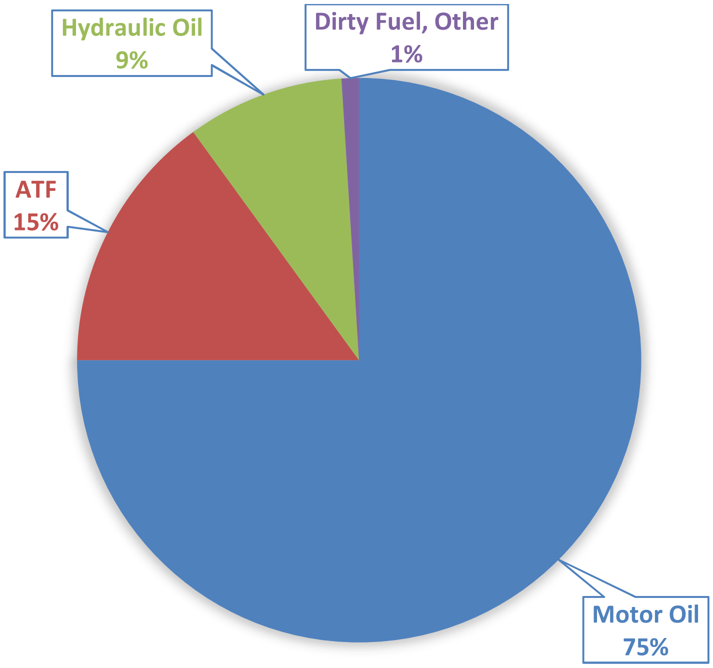


Figure 5 - Model of Estimated Average WMO Collection Tank Constituency

Drawbacks

Disposing of WMO may result in harmful contaminants polluting air or water. Through the process of combustion, contaminants are released into the air which can have harmful effects such as acid rain, as well as general human and animal health issues. Contaminants and their probable sources are listed below in in Table 2 which is adapted from a 2001 journal article by M. El-Fadel and R. Khoury title *Strategies for Vehicle Waste-Oil Management: A Case Study*. The study was carried out in Lebanon and included high levels of lead due to leaded gasoline. Since this is no longer a concern, the lead levels were excluded (El-Fadel & Khoury, 2001).

Table 2 - Contaminants of Potential Concern in Waste Oils (El-Fadel & Khoury, 2001)

Organic contaminants	Probable Source	Approximate Concentration Range[1]
Aromatic Hydrocarbons		
Polynuclear (PNA) Benzo(a)pyrene	Petroleum base stock	360–62,000
Benzo(a)anthacene		870–30,000
Pyrene		1,670–33,000
Monoaromatic Alkylbenzenes	Petroleum base stock	900,000
Diaromatic Napthalenes	Petroleum base stock	440,000
Chlorinated Hydrocarbons		
Trichloroethanes	Chemical reactions during use of contaminated oil	18–1,800
Trichloroethylenes		18–2,600
Perchloroethylene		3–1,300
Metals		
Barium	Additive package	60–290
Zinc		630–2,500
Aluminum	Engine or metal wear	4–40
Chromium		5–24

[1] All values in g/L, except metals in mg/kg (ppm).

Impact of Clean Air Act

According to a policy analysis from the California EPA, an assessment was performed on different used oil management methods, "Used oils contain significantly higher concentrations of heavy metals, sulfur, phosphorus, and total halogens compared to low-sulfur crude-based heavy fuel oils. Because of a generally low quality as fuel, used oil is commonly blended with other fuel oils before use. With blending, the specific level of contaminants in the finished fuel is lowered to an acceptable level for equipment specifications and temporal emission limits for any given user. Combustion of a blended fuel is assumed to not affect the net release of emissions with time; that is, from a life-cycle perspective, the net emissions per unit of used oil consumed remain the same regardless of dilution" (Boughton & Horvath, 2004).

Metals Analysis

The effects of metals contamination may have negative effects on air quality and pose a risk to human health. To determine metals content, spectrochemical analysis ASTM Method D5185 was employed with the use of Inductively Coupled Plasma – Atomic Emission Spectrometry (ICP-AES). The samples were digested with nitric acid prior to analysis. The EPA requires that use of this method be restricted to use by, or under supervision of spectroscopists appropriately experienced and trained in the correction of spectral, chemical, and physical interferences.

As described by tribologist Ashley Mayer in her journal article *4 Oil Analysis Tests to Run on Every Sample,* "ICP spectroscopy is perhaps the most important and useful test in used-oil analysis, but it does have limitations. A key drawback is the size limit of the particles it can vaporize. It does not detect particles beyond the five- to eight-micron range" (Mayer, 2006). This is a problem because that particle size range is the most damaging to engine systems. It is assumed the engine's stock filtration system will address these medium sized particles, but without the ability to determine what is present in this size range, ICP spectroscopy cannot give a clear picture of potential engine damage. There are other test methods available for determining particle size and distribution in a fluid, but the researcher was unable to arrange such tests due to lack of time and local resources. This was a major drawback to the endgame of this thesis, but leaves a starting point for a future researcher to address.

Criteria of Fuels

Diesel fuel is a complex mix of thousands of compounds, most of which are members of the paraffinic, naphthenic, or aromatic class of hydrocarbons. Each class has different physical and chemical properties. Different relative proportions of these three classes make diesel fuels different depending on the supplier (Bacha et al., 2007).

With this wide range of physical and chemical properties all branded under the diesel fuel umbrella, what makes the fuel acceptable for use? How is that defined? And when there is a potential to unintentionally add contaminants, how dirty is too dirty? When attempting to filter out contamination, how clean is clean enough? What happens if a less-than-acceptable fuel is used? Cummins, Inc published a manual on operating the BPU series generators (Cummins, 2015). The manual describes substitute fuels and state that diesel fuels, commercial fuel oils, kerosene, and jet fuels are generally within prescribed limits. What are these prescribed limits?

In 2017, Cummins published an updated service bulletin titled *Fuel for Cummins Engines* which was written to help their engineers and customers alike understand proper fuel selection and problems associated with less-than-desirable fuel conditions. The bulletin describes the "required" diesel fuel specifications, adapted in Table 3 below, to provide the highest efficiency, performance, and reliability with the lowest maintenance costs. However, the most useful section for this research effort is the description of "contingency" diesel fuels (Cummins, 2017). This table will be the standard against which to measure WMO blends. In cohesion with this thesis' research questions, the goal was to determine if a 5% WMO blend fits within these acceptable fuel parameters while balancing air emissions and engine wear characteristics.

Table 3 - Required Fuel Specifications for Cummins Engines (Cummins, 2017)

	Required Diesel Fuel (2017)[1]	Contingency Diesel Fuel (2017)[2]
Kinematic Viscosity	1.3 to 4.1 centistokes at 40°C	1.3 to 13.1
Cetane Number	42 minimum above 0°C 45 minimum below 0°C	35 40
Sulfur Content	Not to exceed 5000ppm [based on region] 15ppm for ULSD[a]	20,000ppm Catalyst equipped engines will be damaged
Sodium Content	0.5ppm maximum	10ppm
Water & Sediment	Not to exceed 0.05 volume-percent	0.5 volume-percent
Carbon Residue	Not to exceed 0.35 mass-percent on 10 volume-percent residuum	Not to exceed 5.0 mass-percent on 10 volume-percent residuum
Density	0.816-0.876 g/cc at 15°C	0.750-0.965
Cloud Point	Should meet lowest expected ambient temp	6°C below lowest ambient temp for expected operation
Ash	Not to exceed 0.01 mass-percent	0.05 mass-percent
Distillation	90 volume-percent at 360°C The distillation curve must be smooth and continuous	90 volume-percent at 395°C
Lubricity HFRR	520 micron maximum Wear Scar Diameter at 60°C	600 micron[3]
Heavy Metals		Vanadium 5ppm max Aluminum 1ppm max Silicon 1ppm max

[1] Ultra Low Sulfur Diesel – Required in all highway diesel vehicles as of 2006.

[2] Additional maintenance may be required when using contingency fuels.

[3] A lubricity additive **must** be used if the fuel does not meet the minimum lubricity specification.

Vintage Diesel Systems

Diesel engines were invented in 1880s Germany by Rudolph Diesel. The concept is different than gasoline engines in that it uses compression ignition instead of spark ignition. The principle relies on introducing the fuel to the combustion chamber under much higher pressure than in gasoline engines. Fuel injection methods improved under the engineering help from Bosch, GmbH which still supplies fuel injection systems today.

A basic diesel engine operates on direct injection where the piston draws in air and compresses it. At the end of the compression stroke, the fuel is injected directly into the cylinder under high pressure then auto-ignition commences.

The concept of a diesel engine being omnivorous, or “multifuel-capable”, dates back to experimentation tried by the inventor himself. Primitive diesel engines were tried with vegetable oils, peanut oil, and even coal dust.

To further this multifuel capability, Continental Aviation & Engineering Corporation was contracted by the U.S. Army Ordnance Corps in the 1950s to develop the LD-465 (naturally aspirated) and LDS- and LDT-465 (turbosupercharged) “multifuel” engines. These engines, shown in Figure 6, hosted state-of-the-art principles and components that enhanced the Army’s capability to burn a wide range of fuels as it applied in their newest two-and-a-half- and five-ton cargo trucks, as shown in Figure 7.

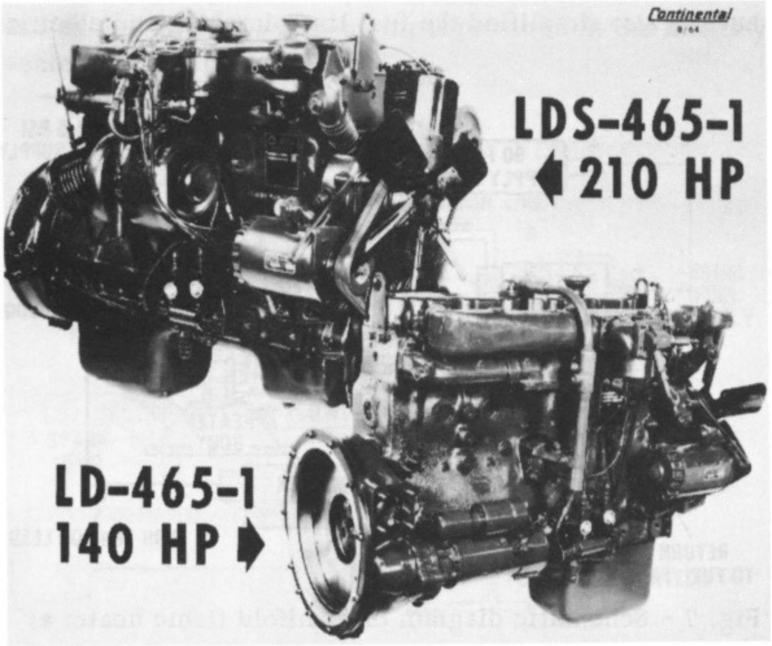


Figure 6 - Multifuel Engines Developed in 1955 for the U.S. Army (Isley, 1967)

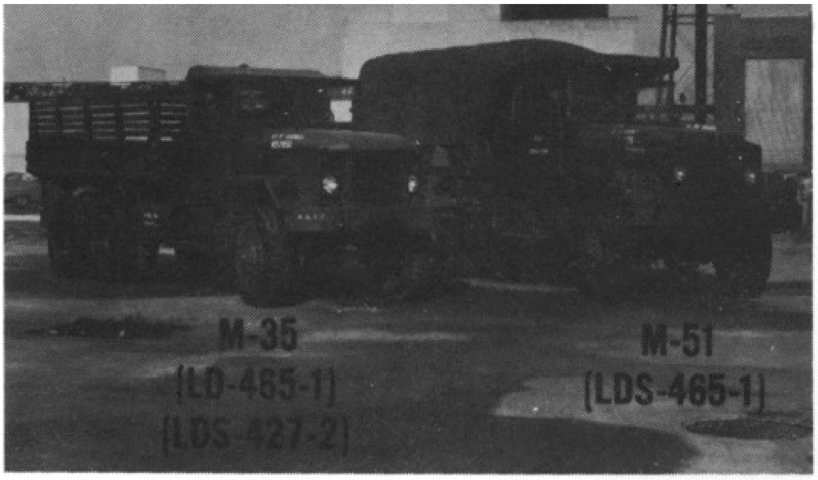


Figure 7 - Comparison of M-35 and M-51 U.S. Army trucks (Isley, 1967)

The engines utilized the principle of Hypercycle combustion. Developed at M.A.N., a German diesel engine manufacturer, J.S. Meurer summarized Hypercycle combustion in 1955 as “a system that introduces fuel by depositing it in the form of a thin liquid film onto the walls of a spherical combustion chamber which is centrally located in the piston crown. Formation of fuel layers is assisted by strong swirling action of the combustion air, which in today's design is generated by means of specially shaped intake ports. Combustion then takes place after gradual and progressive evaporation of the fuel from the combustion chamber walls at surprisingly low rates of pressure rise" (Meurer, 1967). This system design can be visualized in Figures 8 and 9.

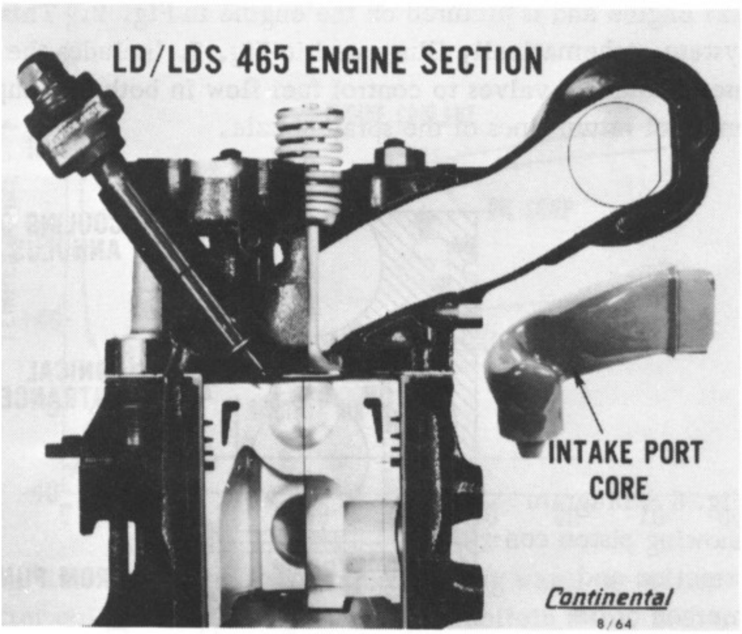


Figure 8 - Major Components of the LD/LDS/LDT-465 Engine (Isley, 1967)

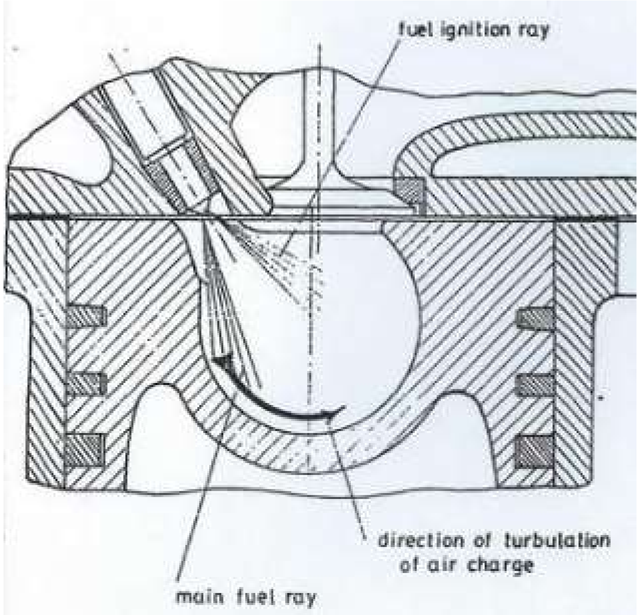


Figure 9 - Spherical Combustion Chamber in Multifuel Engine Piston (Elkotb, 1980)

The added components consisted of air intake swirl ports, a heated air intake manifold, and a fuel density compensator, which assisted the fuel delivery characteristics with changes in fuel viscosity (Shipinski et al., 1967)(Isley, 1967). Besides add-on hardware, the multifuel LD/S/T-465 operated at a 22:1 compression ratio, much higher than other diesel engines in its class (U.S. Army, 1981). This was achieved by more robust construction of engine components and helps to reduce ignition delay (Shipinski et al., 1967). The combination of these components and combustion principles enabled these vintage engines to handle a variety of fuels without fear of catastrophic damage or accelerated component wear. To show just how multifuel-capable these engines were, refer to Table 4, which is copied from the Operators Manual for the U.S. Army M35A2 2-1/2-ton truck that was powered by the LDT-465 engine from the 1950s until the truck was retired in the late 2000s (U.S. Army, 2006).

Table 4 - Permissible Fuels for M35A2 Multifuel Engine (U.S. Army, 2006)

Fuel	**Lower Temperature Limit (Do Not Use Below This Temperature)**
Primary Fuels	
Diesel fuel, VV-F-800, grade DF-2 (NATO code no. F-54)	+32 °F (0 °C)
Diesel fuel, VV-F-800, grade DF-1 (NATO code no. F-54)	-10 °F (-23 °C)
Diesel fuel, VV-F-800, grade DF-A (NATO code no. F-54)	Can be used at all temperatures.
Alternate I Fuels	
Turbine fuel, MIL-T-5624, grade JP-5 (NATO code no. F-44)	-51 °F (-46 °C)
Distillate fuel, MIL-F-24397, ND (NATO code no. F-85)	+40 °F (+4 °C)
Commercial diesel fuel (ASTM D975) 2-D and no. 2	+32 °F (0 °C)
Diesel fuel, MIL-F-16884 (NATO code no. F-75 or F-76)	+15 °F (-9 °C)
Commercial diesel fuel (ASTM D975) 1-D and no. 1	-10 °F (-23 °C)
Turbine fuel, aviation, MIL-T-38219 grade JP-7	-46 °F (-43 °C)
urbine fuel, aviation, kerosene type, MIL-T-83133, grade JP-8 (NATO code no. F-34)	-58 °F (-50 °C)
Aviation gasoline, MIL-G-5572, AVGAS 80/87 (NATO code no. F-12)	-76 °F (-60 °C)
Commercial aviation gasoline (ASTM D910) grade 80/70	-72 °F (-58 °C)
Commercial gasoline, leaded, low lead or unleaded, when research octane number is 89 or below, or octane number displayed on retail gasoline pumps in CONUS is 85 or below	*
Commercial aviation turbine fuel (ASTM D1655), jet A	-40 °F (-40 °C)
Commercial aviation turbine fuel (ASTM D1655), jet A-1	-52 °F (-47 °C)
Any mixture of primary and/or alternate I fuels listed above.	*
Alternate II Fuels	
Turbine fuel, MIL-T-5624, grade JP-4 (NATO code no. F-40)	-72 °F (-58 °C)
Turbine fuel, aviation, naphtha-type (ASTM D1655), jet B	-58 °F (-50 °C)
Gasoline, unleaded/low-leaded, VV-G-001690, special grade (91/82)	*
Combat gasoline, MIL-G-3056, MOGAS (NATO code no. F-46)	0 °F (-18 °C)
Gasoline, automotive (NATO code no. F-50)	*
Gasoline, W-G-76, regular and premium grades	*
Gasoline, unleaded/low-leaded, VV-G-001690, regular and premium grades	*
Aviation gasoline, MIL-G-5572, AVGAS 100/300 (NATO code no. F-18)	-75 °F (-59 °C)

Commercial aviation gasoline (ASTM D910), grade 100/130	-72 °F (-58 °C)
Commercial gasoline (ASTM D439), leaded, low- lead, or unleaded, where research octane number is above 90, or octane number displayed on retail gasoline pumps in CONUS is above 86	*
Any mixture of alternate II with primary, alternate I, and/or alternate II fuels listed above	*
Emergency Fuels	
Burner fuel oil, VV-F-815, grade FO-1	0 °F (-18 °C)
Burner fuel oil, VV-F-815, grade FO-2	20 °F (-7 °C)
Commercial burner fuel oil (ASTM D396), grade FO-1	0 °F (-18 °C)
Commercial burner fuel oil (ASTM D396), grade FO-2	20 °F (-7 °C)

*Any temperature at which fuel will flow.

Modern Diesel Systems

Many advancements have been made in diesel engine technology in the latter half of the 20th century. Advances have been made in efficiency, longevity, and power. And because of environmental concerns, some of those efforts have even been hampered with the strict EPA regulations rolled out in a tier system as manufacturers can catch up to the changing air and noise pollution policies.

Vintage injections systems were only capable of a few thousand pounds of pressure, but developments in common rail injection direct injection systems have increased that pressure tenfold. Today’s injection systems operate in the 20,000 to 40,000psi range.

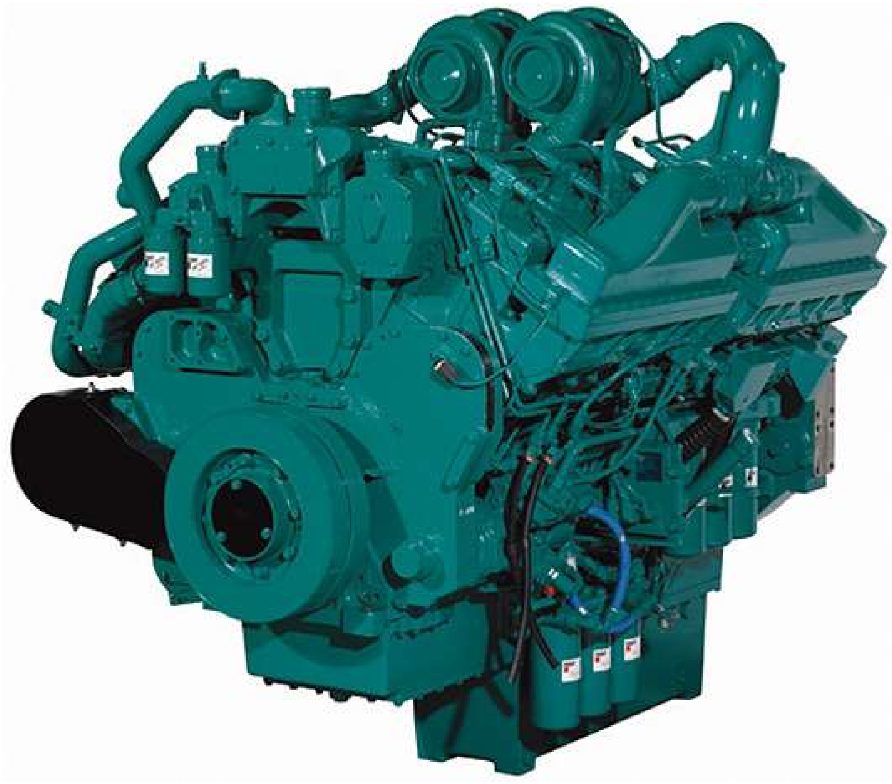


Figure 10 - Cummins QSK38-G5: Powerplant of the BPU

Some modern diesel engine fuel systems even utilize optical fuel sensors to detect if the fuel is too dirty for use. If a dirty fuel is detected, the computer shuts down the engine to protect it. If a device like this existed on a military engine, it would need to be defeated with software or explicitly excluded when writing the equipment contract specifications.

Engine Component Wear

Generally speaking, long operation on contingency fuels may cause early clogging of fuel filters or early fouling of fuel injector nozzles (U.S. Army, 1981).

Photographs in Figure 11 show the effects of running a much higher concentration WMO blend in a vintage multifuel engine. In 2014, a private military vehicle owner was rebuilding a 1984 LDT-465 engine and he documented the residue and wear on the combustion-related components. The engine had reportedly been run on a custom WMO blend. In this owner's case, the WMO was cut 4:1 with gasoline to thin the viscosity to a comparable level to diesel fuel, resulting in a 60% WMO, 25% diesel, 15% gasoline blend (T. Duncan, email interview, 24 Jan 2017).

In consideration of this thinning method, Chevron Corporation's 2007 *Diesel Fuels Technical Review* states "One percent or less of gasoline will lower the flash point of a gasoline/diesel fuel blend below the specification minimum for diesel fuel. This will not affect the fuel's engine performance, but it will make the fuel more hazardous to handle. Larger amounts of gasoline will lower the viscosity and/or cetane number of the blend below the specification minimums for diesel fuel. These changes can degrade combustion and increase wear" (Bacha et al., 2007). But this is strictly in regards to mixing with pure diesel fuel, not with added motor oil first. Adding to this judgement call, Cliff Burbrink, a fuel chemist for Cummins agrees that the use of gasoline as a thinning agent may be acceptable for a vintage multifuel engine, but adding gasoline to a modern diesel system changes make the fuel flammable for a system that was not designed to handle it (C. Burbrink, email interview, 3 Feb 2017). Additionally, this research looks at a blend ratio so low that thinning may not be necessary to assist combustion characteristics. The only concern that thinning may help address would be in the filtering process to assist in flow through a filtration device, which will be discussed later in this chapter.

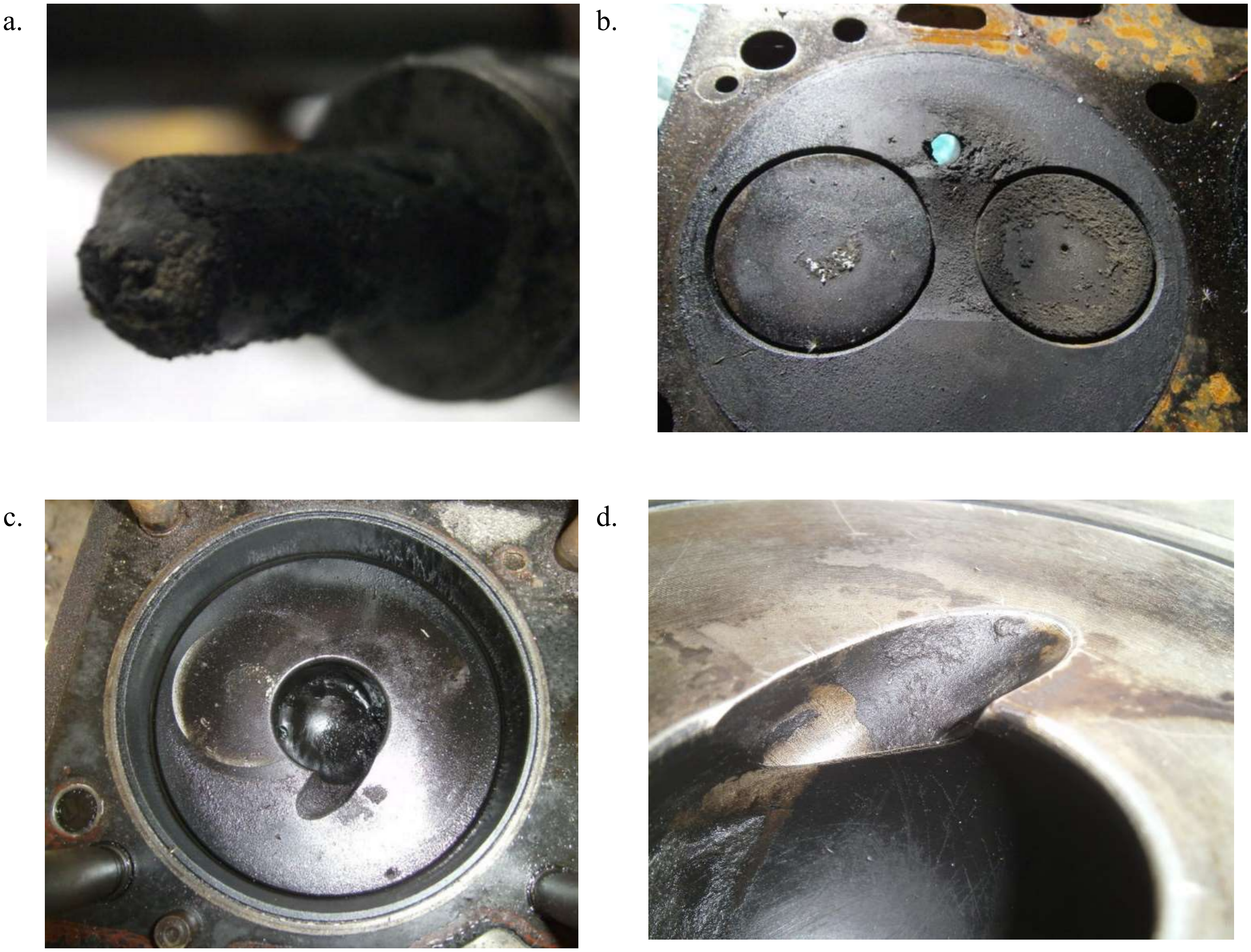


Figure 11 - Effects from WMO Blends on LDT-465 Components (Duncan, 2014)

An example of one of the injectors is shown in shown in Figure 11a, the intake and exhaust valves in Figure 11b, and the crown jewel of hypercycle combustion: the bottom portion of a spherical combustion chamber in Figure 11c. All six injectors showed the same level of heavy residue but were left unaltered and tested in a pop tester. The break pressures ranged from 2,000 to 2,800psi. After cleaning, the injectors all achieved 3,100psi. The valves showed normal carbon residue buildup as can also be seen on the piston head around the spherical combustion chamber.

In Figure 11a, the deposits on the exterior of the injector nozzle are plainly seen. What is not seen is any possible pitting or scarring on interior of the nozzle. As injector nozzles wear down over time, spray pattern can be affected, which will lead to reduced atomization and degraded burn characteristics, which ultimately reduces engine power and efficiency. An example of injector wear results can be seen in Figure 12.

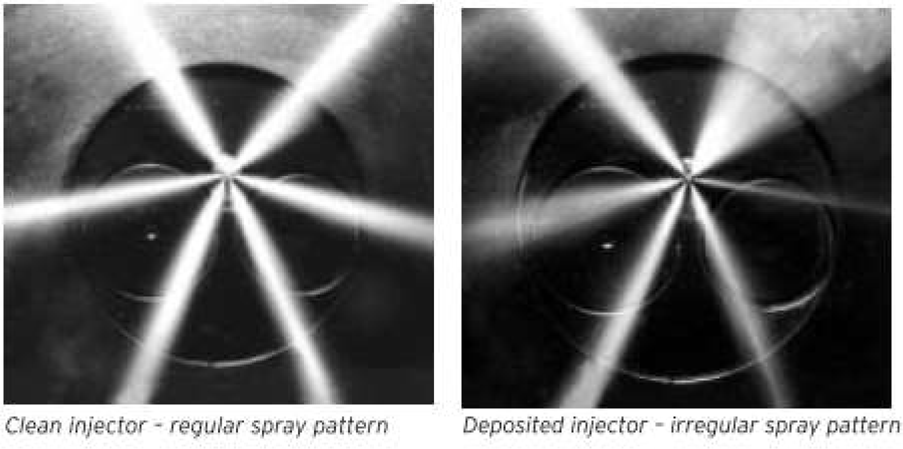

Clean injector - regular spray pattern *Deposited injector - irregular spray pattern*

Figure 12 - Fuel Spray Pattern

The main causes of fuel system component wear are low fuel lubricity and contaminants in the fuel source. The contaminants can be of any form, but are typically silica and alumina compounds (or dust and dirt) in the fuel. When introducing WMO to the fuel blend, there is inherent risk of introducing wear metals, water, and other contaminant particles as well. The particles entrained in the high pressure fuel essentially act as a sandblasting media as it passes through the pumps and injectors. The most damaging particle sizes are in the 2-10 micron range. They are also the most difficult to filter out. On the older multifuel engines, the tolerances were relatively higher, so this micron range did not affect the fuel system components as much. But in modern high pressure fuel systems, the particles can have a devastating effect.

As can be seen in Table 3, the 2017 Cummins service bulletin calls out four specific heavy metals: vanadium, aluminum, silicon, and sodium. Elevated levels of vanadium can cause valve burning. Aluminum, silicon, and sodium can cause premature ring and liner wear, which can lead to excessive oil consumption. Additionally, although not called out on the table, the service bulletin mentions that high levels of zinc can cause injector spray hole carboning (Cummins, 2017).

Filtering Methods

Motor oils of any kind are designed to clean, cool, and lubricate the mating of two moving metal surfaces. Inevitably, the metal surfaces will wear down over time and fine metal particles will end up in the oil. This oil is periodically changed out then discarded. The reuse of this discarded waste oil to burn in a heater causes no damage to the heater components, but when used as a fuel in modern high pressure direct injection systems in diesel engines, the particles can cause wear and eventual catastrophic failure to pumps and injector nozzles. The metal particles act as a blasting media; therefore, they need to be filtered out. Since even the best filters are only about 98% efficient, it is impossible to remove all contaminants. Therefore, the particles only need to be filtered down to a small enough size and concentration to pass through the fuel system without causing damage. In most engine applications, the limiting factor is the injector nozzle orifice size. All diesel engines have fuel filters mounted onboard and most have more than one. They are combined in series with decreasing size ratings. Cummins has selected a series of 5- and 2-micron rated filters as the stock equipment on the QSK38 model – therefore, 2 microns will be the target for success when measuring particle size after cleaning with the centrifuge (Cummins, 2017). Anything larger than 2 microns should be filtered out by the engine's filter system but should not be relied upon for primary dependence. Anything smaller than 2 microns is considered successfully filtered. Without proper filtering, deposits may build up on injector nozzles and cause irregular spray patterns as can be seen from the photos in Figure 12 (Bacha et al., 2007). However, Cliff Burbrink (Cummins), states that filters have limited effect on nozzle deposits. Nozzle coking is predominately a function of temperature, contaminants in the fuel such as zinc, and the presence of detergents in the fuel. When adding WMO to fuel, the oil additives and contaminants can react to other contaminants in the fuel which will lead to chemical compounds that coke the nozzles quickly. This is of greater concern than the effects nozzle scoring from particles will have. Nonetheless, large particles can damage the pilot valve seat of the injector which will negatively affect the amount of fuel that gets injected, as displayed in Figure 12 (Burbrink, 2017).

Filter elements, fuel screens in the fuel pump, and fuel inlet connections on injectors must be cleaned or changed whenever contaminated. These screens and filters, in performing their intended function, become clogged when using a poor or dirty fuel, and will need to be changed more often. The standard fuel filter is the spin-on element. These filters contain a porous, pleated, chemically treated paper element that will pass fuel freely but trap impurities and sediment. When the element is serviced, it is simply detached from the fuel filter head assembly, discarded, and replaced with a new element (Cummins, 2017).

Engine wear metals are expected to be found in WMO. It is beneficial to pre-filter the WMO before blending with diesel fuel. This research will determine if it is required in a military power generator application.

There are several different methods that can be used to clean WMO prior to use as an alternative fuel. They have varying degrees of effectiveness and associated costs. The methods are detailed below in order of increasing complexity.

Status Quo

Do nothing at all. It costs nothing. The user simply collects WMO in a container and pours it straight into the fuel tank. The only effort involved is in the collection itself. If the history of the WMO is absolutely known, then this option is viable. However, the uncertainty of contamination and hydration is the highest.

De-watering

WMO may contain traces of water. If the user obtains emulsified WMO or a batch containing significant amounts of water or antifreeze, it is best to discard of the WMO to a proper recycling facility. However, trace amounts of water can be mitigated. Gravity, time, and heat will be the most beneficial. Whether the user plans to filter the batch or not, consideration should be given to de-watering. The easiest method is to simply allow time for gravity to separate oil from water. Then, pump the oil from the top while avoiding the layer of water at the bottom.

A second method is to pump the batch through an oil/water separator like most diesel engine fuel systems incorporate already. They can be obtained in a spin-on filter form and are readily available at automotive parts stores.

A third method is to boil the water off. Heat can be applied to get the batch up to the boiling point of water while remaining below the flashpoint of oil. This can be dangerous if the user is not well-versed in petroleum product safety and is more energy intensive, but can prove more effective at removing all hydration from the WMO batch.

Gravity Filter

With a gravity filter, the user can do one of two common methods, or both. By collecting WMO in a container and allowing the mix to sit over time, many particles and water will settle out on their own. Applying heat can accelerate this process.

A second method is filter bags. The bags can be made in different straining sizes. Filter bags are typically used more for WVO, when there is a need to filter larger organic contaminants like fry batter. However, bags can be found with ratings from 1000 micron down to 1 micron. This method will require a series of bags in successive sizes to ensure the smallest bag is not clogged too quickly.

Forced Filter

Most automotive applications pump fuel through inline spin-on cartridge filters. A simple platform can be rigged to contain a series of filters, typically from 50 microns down to 1 micron. The smaller range of filtering ability assumes the fuel source is considered clean to begin with. With a filter setup like this, it is wise to use a water separator as the first in the series. The filters will need to be changed every few hundred gallons.

Centrifuge

A bowl-type centrifuge is a bowl that spins at approximately 6000 rpm. The bowl has no bottom, just cupped side walls shown in Figure 13. WMO is introduced through a drip valve into the spinning bowl. The centripetal force due to centrifugal motion causes the WMO to be pushed up against the walls of the bowl. Heavier particles will stay against the wall while the good oil rises to the top towards the hole in the middle then will drop out into a container below. This drip process is very slow and the motor turning the centrifuge requires constant power for hours. The process may need to be stopped periodically to disassemble the bowl for cleaning. This involves scraping sludge from the bowl. This sludge will probably be surprising to the user as to how much contamination could have been missed by other methods previously mentioned. A centrifuge process can typically filter down to the sub-micron level, but is the most effort and time intensive, as well as having the highest setup cost.

Figure 13 - Bowl-Type WMO Centrifuge (Chastain, 2010)

A spinner-type centrifuge works on the same principle as the bowl-type, but is powered by oil pressure supplied from a separate pump. Pressurized oil is pumped through the rotor and the velocity of exiting oil through jet nozzles powers the centrifuge. This type of filtering method was chosen because it was already available from a previous student's research. It is explained in further detail in Chapter III.

Conclusion

WMO can be collected and burned as a diesel fuel supplement. Exhaust emissions are of particular concern due to metals contamination and high sulfur contents. Engine wear can possibly be accelerated due to use of oil in fuel, but is minimized by lowering the blend ratio. It is feasible and encouraged to recycle WMO into a fuel supplement in diesel generators at deployed locations.

III. Methodology

Introduction

Now that the foundation has been laid for burning WMO in a diesel engine, the development of a testing method will be discussed. The purpose of this chapter is to explain methods used to obtain data that will support or refute feasibility of WMO burning. This study will take an extensive look at fuel quality, potential engine damage, exhaust emissions risks, and how to clean used oils. All data will be analyzed then summarized in the subsequent chapters.

Analytes of Concern

The researcher initially started developing a list of analytes to test for per findings in the literature review, but due to several challenges in the local lab, the decision was made to contract out the work to ALS Global, Inc, a tribology services company with several labs worldwide. Because this data acquisition route was chosen, the researcher accepted the standard analytes tested in ALS Tribology's in-service lubricant condition monitoring service package. This included twenty metals, kinematic viscosity, and the content of water, coolant, or soot. The metals included in the test were as follows: Iron (Fe), Chromium (Cr), Lead (Pb), Copper (Cu), Tin (Sn), Aluminum (Al), Nickel (Ni), Silver (Ag), Titanium (Ti), Vanadium (V), Silicon (Si), Sodium (Na), Potassium (K), Magnesium (Mg), Calcium (Ca), Barium (Ba), Phosphorus (P), Zinc (Zn), Molybdenum (Mo), and Boron (B).

Iron, chromium, lead, copper, tin, aluminum, nickel, silver, titanium, and vanadium are all wear metals. These metals indicate wear on particular components in an engine. The condition of the donor engine has no bearing on this research, but a basic understanding of why these metals appear in WMO is necessary. Silicon, sodium, and potassium are considered contaminants in the realm of lubricants. They can be an indicator of both internal and external contamination. The presence of silicon generally indicates dirt while sodium and potassium are present in engine anti-freeze and cooling systems which can help detect the presence of coolant in the oil. Magnesium, calcium, barium, phosphorus, zinc, molybdenum, and boron are all additives in oils. They are blended into oils in different forms and quantities to change the characteristics the manufacture is trying to achieve (ALS Tribology, 2009). With that explained, none of the implications these metals indicate will be relevant to this research. Instead, the two main concerns presented by the presence of these metals is engine component wear and toxic emissions into the environment from combustion. Knowing the concentrations and size of these elements is a crucial step towards understanding the benefits and drawbacks of using WMO as a fuel.

There were a few other irrelevant tests provided by ALS Tribology, namely PQ Index, Total Base (or Acid) Number, and fuel content that were not used in this research.

In addition to all the analytes listed above, the researcher wanted to test particle size and concentration. Due to the unavailability of testing equipment, the researcher relied on a more qualitative approach by viewing a few samples with a scanning electron microscope. This will be discussed more in the electron microscopy section of this chapter.

Sample Collection

In real world application, the WMO would be collected directly from the barrels and tanks in the maintenance shops. However, once the waste oils are poured into the collection tank, it is impossible to determine the constituency. Recall the discussion about Figure 5 in Chapter II. To make this research more scientific and to eliminate many unknowns, the oils chosen were collected directly from the crankcases of several vehicles, skipping the collection tanks. Wright-Patterson Air Force Base's 88th Logistics Readiness Squadron (88LRS) provided several test samples from their Government-Owned Vehicle (GOV) fleet. The samples represent a mix of vehicles to include pickup trucks, a commercial bucket truck, and a van. Samples were obtained from both gas and diesel engines. SAE 5W30 oil was used in the gas engines and SAE 15W40 was used in all diesels. The years of the GOVs ranged from 2003 to 2011.

In addition to the five WMO samples provided by 88LRS, the researcher provided three instances of previously recorded data from his personal vehicles as well as a new sample of ATF from his personal vehicle to be sent in to the lab for testing. The researcher also provided three WMO samples from a collection barrel that contained a variety of oils from various vehicle maintenance service activities. The WMO barrel had a built-in cartridge filter mechanism which will be explained in more detail in the cartridge filtering section of this chapter. Seven of the used oil samples were filtered with a centrifuge. Finally, two samples of virgin motor oil and two samples of diesel fuels were supplied by 88LRS bringing the total number of samples analyzed for this study to twenty-three. All samples were analyzed by ALS Tribology labs.

Samples of the virgin and waste motor oils, ATF, and diesel fuels were collected in 1-liter wide mouth high-density polyethylene (HDPE) bottles. In the case of motor oil, two main types were collected: SAE 5W-30 from gasoline engines and SAE 15W-40 from diesel engines. Both were conventional mineral-based oils, meaning they were not synthetic. The transmission fluid was DEXMERC, a specific type of ATF. The two diesel fuels collected were No. 2 diesel and B20, which is a blend of 20% biodiesel and 80% petroleum diesel. See Table 5 below for further sample collection parameters and number of samples collected for each type. To prevent contamination from sediment, water, or antifreeze, the samples were collected directly from the fluid drain ports (i.e. crankcase pan drain). Each sample bottle was catalogued by the donor vehicles' model and usage data. All samples were assigned a simple letter code or nickname. More vehicle details can be seen in Table 6. More details can be found in Appendix A.

Table 5 - Sample Fluid Category Matrix

Category	Type	Condition	N
Motor Oil	SAE 15W-40	Virgin	1
		Waste	6
		Filtered	3
	SAE 5W-30	Virgin	1
		Waste	2
		Filtered	2
	Various from WMO barrel	Waste	2
		Filtered	3
Fuel	No. 2 diesel	Virgin	1
	B20 biodiesel	Virgin	1
Transmission Fluid	DEXMERC	Waste	1

Table 6 - WMO Sample Source Details

Unit Name	Other info	Unit Make Name	Unit Model	Year of Mfg	Compartment Make Name	Compartment Model Name	Compartment Type	Fluid Grade
Deuce	Used	Kaiser-Jeep	M35A2	1970	Continental	LDT-465	Diesel Engine	SAE 15W40
Chevy	Used	Chevrolet	2500HD	2005	Duramax	LLY	Diesel Engine	SAE 15W40
Bobber	Used	Kaiser-Jeep	M35A2	1971	White	LDT-465	Diesel Engine	unknown
A	Used	Chevrolet	3500	2003	Vortec	6000	Gas Engine	SAE 5W30
B	Filtered	Chevrolet	3500	2003	Vortec	6000	Gas Engine	SAE 5W30
C	Virgin, Oil	--	--	--	--	--	--	SAE 5W30
D	Virgin, Oil	--	--	--	--	--	--	SAE 15W40
E	Used	Chevrolet	3500HD	2011	Duramax	LML	Diesel Engine	SAE 15W40
F	Filtered	Chevrolet	3500HD	2011	Duramax	LML	Diesel Engine	SAE 15W40
G	Used	International	Bucket Truck	2005	Navistar	DT466	Diesel Engine	SAE 15W40
H	Filtered	International	Bucket Truck	2005	Navistar	DT466	Diesel Engine	SAE 15W40
I	Used	Ford	F350	2012	Ford	Powerstroke	Diesel Engine	SAE 15W40
J	Filtered	Ford	F350	2012	Ford	Powerstroke	Diesel Engine	SAE 15W40
L	Virgin, Diesel	--	--	--	--	--	--	No. 2
M	Virgin, Biodiesel	--	--	--	--	--	--	B20
N	Used	Chevrolet	3500 Van	2003	Vortec	6000	Gas Engine	SAE 5W30
O	Filtered	Chevrolet	3500 Van	2003	Vortec	6000	Gas Engine	SAE 5W30
P	Used	various	various	various	WMO Barrel	Top	various	various
Q	Filtered	various	various	various	WMO Barrel	Top	various	various
R	Used	various	various	various	WMO Barrel	Bottom	various	various
S	Filtered	various	various	various	WMO Barrel	Bottom	various	various
T	Filtered	various	various	various	WMO Barrel	Bottom	various	various
U	Used ATF	Chevrolet	2500HD	2005	Suncoast	GMAX 5	Auto Trans	DEX/MERC

*Items in blue were analyzed separately from 2011 – 2016 by ALS Tribology at the researcher's personal request.

*Items in red were analyzed in one batch by ALS Tribology in December 2016.

Sample Preparation

Determining what contaminants are in the dirty oil compared to what can be removed by filtering is key to decision-making when it comes to trusting available methods of mitigating contaminants. The two methods used to filter oil in this research, a spinner-type centrifuge and a more traditional setup of cartridges, were chosen due to availability and practicality as needed in a contingency environment. The two methods are further explained below.

Centrifuge

After the oil samples were taken to AFIT's laboratory, they were prepared for testing. Before filtering the oil, 50mL samples were drawn from each container with a large pipet and placed in centrifuge vials, marked, then set aside for later testing. Virgin oil containers were then re-labeled as "flush" oil and were to be used only as a centrifuge system flush before filtering a new sample of different weight. The samples can be seen below in Figure 14. All WMO samples were individually cycled through a spinner-type centrifuge on a continuous loop for ten minutes to remove particles. The lab setup shown below in Figure 15 was crafted by the researcher and AFIT's machine shop personnel using parts scavenged off a Waste Vegetable Oil (WVO) centrifuge rig purchased from Fryer-to-Fuel, LLC in 2008 for another student, Capt Harvey Gaber's research in recycling fryer grease on base to use in diesel vehicles (Gaber, 2009).

Parts scavenged from the WVO rig included a ½ hp motor, carbonator gear pump, dial pressure gauge, and spinner-type centrifuge with base mount. The rig had been in storage at the base recycling center for six years so the pump, lines, and filters were completely gummed up with rotten congealed fryer grease. The researcher deep cleaned the pump components with brake cleaner and mineral spirits. It was decided that the centrifuge was not salvageable, so a new replacement was purchased from Fryer-to-Fuel, LLC. Also, new hydraulic hose and fittings were procured locally from a hydraulic supply store. The rig components were given to the AFIT machine shop for final assembly where a stand was made from 80/20 T-slotted extruded aluminum to fasten the pump and centrifuge to a sturdy surface while allowing a container to fit underneath.

Figure 14 - WMO Sample 50mL Vials

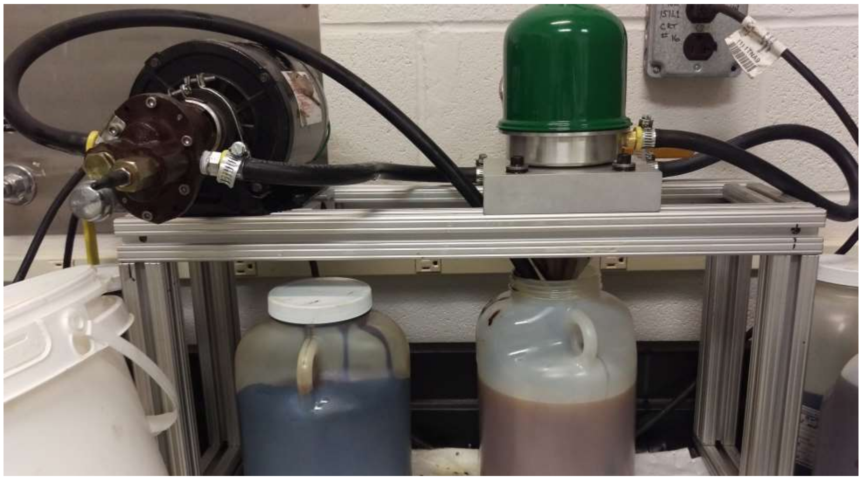


Figure 15 - WMO Centrifuge Rig

This particular model of centrifuge is a spinner-type. It is not driven directly by a motor, but instead is powered by the force of the pumped oil itself. A sample of virgin oil was used first to flush the system since there was a capacity which could not be fully drained or cleaned before running a new sample. The flush oil used in each case was the same weight as the WMO to be filtered. A container was placed below the centrifuge, as can be seen above in Figure 15. The suction hose was pushed to the bottom of the container and a metal funnel placed between the container and centrifuge discharge port. When the pump was powered on, the oil traveled to the pressure gauge, which registered 80psi. Then the oil travelled onward to the centrifuge. It was pumped into a channel cut in the base of the centrifuge and through a hollow spindle in the rotor. This is detailed in Figure 16. The rotor then fills with oil and exits through two opposing angled orifices at the bottom of the rotor. This begins to turn the rotor using the principle of jet propulsion. Within a couple seconds, the rotor achieves full speed of about 8000 rpm (Fryer-to-Fuel, 2016). As the rotor spins, centrifugal force separates the fluid by mass. The heavier particles get pushed to the walls of the rotor and the lighter oil can exit through the center downward towards the exit jets at the bottom. Eventually, the rotor will need to be cleaned after about 150-200 gallons of usage, which was not reached during the period of this research. Approximately six gallons of WMO was filtered during this experiment. After all samples were finished with filtering, the centrifuge was disassembled for cleaning. Particles collected on the wall of the rotor as described previously can be seen in Figure 17. This residual was explored under a microscope as described later.

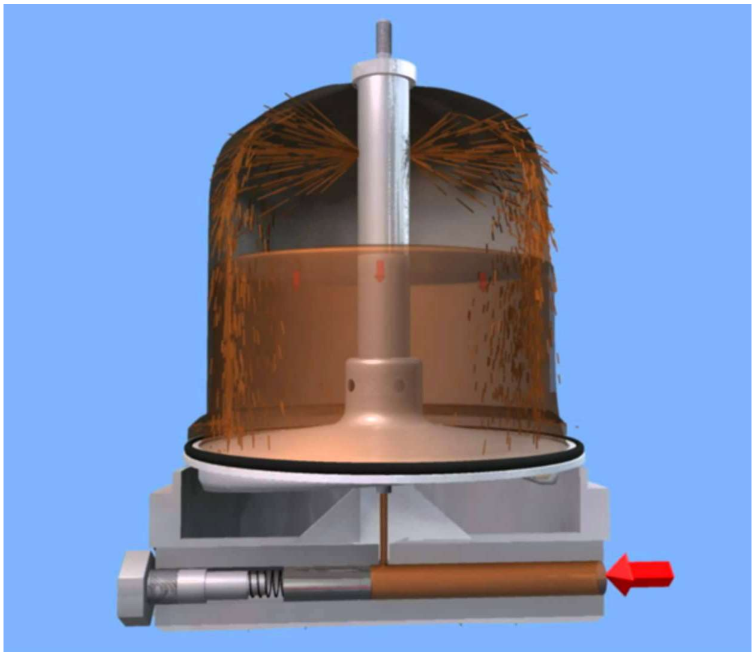


Figure 16 - Cutaway Model of Spinner Type Centrifuge (Autowin, 2011)

Fryer-to-Fuel, LLC recommends heating the WMO prior to filtering, because it helps to lower the viscosity which eases its passage through the centrifuge and allows easier particle separation. As a secondary method, they also recommend if not heating the WMO, then diluting with approximately 20% diesel can help to cut the viscosity. The heating procedure was ignored because on a large-scale filtering process, electricity usage for heating would trump the savings from recycling the WMO for its energy content.

Cutting with diesel was also ignored to prevent cross-contamination without knowing the properties of the diesel fuel also undergoing analysis. While the researcher does not disagree with the effectiveness of heating, cutting with diesel is recommended for any follow-up research moving forward from what was found here. Furthermore, while there was no analysis of power consumption and heater purchase cost, it was determined that heating is likely too expensive to justify the small benefit returned. However, while running the centrifuge, the researcher did make a note that the temperature of the filtered WMO samples upon completion of a ten-minute run were noticeably hot from fluid friction through the pump and centrifuge.

A spinner-type centrifuge is capable of filtering down to one tenth of a micron but is not intended to remove water or antifreeze. In this study, water removal was not of particular concern because the researcher was highly confident the samples provided by 88LRS had not been introduced to water at any point. However, this confidence is key when collecting WMO in bulk. If there is any chance that a WMO barrel has been exposed to water or antifreeze, it is best to dispose of the barrel in traditional methods and not make an attempt to salvage it. After the samples were filtered, they were all compared to their virgin counterparts to assess filter efficiency.

Figure 17 - Residual Particulate Matter in Centrifuge Rotor Cap

Cartridge

When using the cartridge method, WMO sample T (more details in Appendix A) was pumped directly from a collection barrel through a four-filter series consisting of a water separator first, then through paper canister- and metal spin-on-cartridges mounted to a panel above the collection barrel, shown in Figure 18. The paper filters, Baldwin PF906 (primary, water separator) and PF902 (secondary), as seen in Figure 19, all had a nominal rating of 10-microns. Whereas the final stage metal spin-on filter had a nominal rating of 2-microns. The results are shown in chapter IV.

Figure 18 - WMO Collection Barrel with Cartridge Filter Rig

Figure 19 - Baldwin Fuel/Water Separator and Replacement Cartridge Filters

Figure 20 - Waste Drained from Clogged Fuel Filter

Figure 21 - Dirty Fuel/Water Separator Cartridge

Figure 22 - Resulting Clean WMO from Cartridge Filter Rig

Preparation for Analysis

After filtration, the samples were packaged in a kit received in the mail from ALS Tribology. Each sample was placed into 100mL bottles and catalogued with detailed information about each donor source (i.e. vehicle engine type, mileage, age, etc). Then the sample bottles were packaged into cardboard boxes and mailed to the tribology lab in Cleveland, Ohio. The categories of this data associated with each sample, including the results returned from the lab can be seen in Appendix A.

Analytical Methods

Metals Analysis

Metals were determined by ASTM Method 5185. The method covers the determination of additive elements, wear metals, and contaminants in used and virgin lubricating oils and base oils by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES).

Kinematic Viscosity

Kinematic viscosity is the ratio of the dynamic viscosity to the density of a material at the same temperature and pressure. Dynamic viscosity is a measure of a fluid's resistance to flow. Results can indicate physical changes or contamination by other fluids. Kinematic viscosity is measured in mm^2/s, otherwise known as centiStokes, or cSt.

ASTM Method D445 defines the standard test method used (ASTM International, 2016). It summarizes the method as measuring the time for a fixed volume of liquid to flow under gravity through the capillary of a calibrated viscometer dipped in a closely controlled temperature bath to within ±0.02°C as can be seen in Figure 23. Virgin motor oils are measured at both 40°C to represent typical engine startup and 100°C to represent typical engine operating temperatures. Because the tribology lab is setup to analyze properties of used motor oil as they were used as lubricants and not as fuels, the used oils were only tested at 100°C. When WMO is blended and stored with diesel fuel, the 40°C viscosity will matter more. Unfortunately, the 40°C viscosity was not determined except for two virgin motor oils (samples C and D). A workaround is discussed in chapter IV.

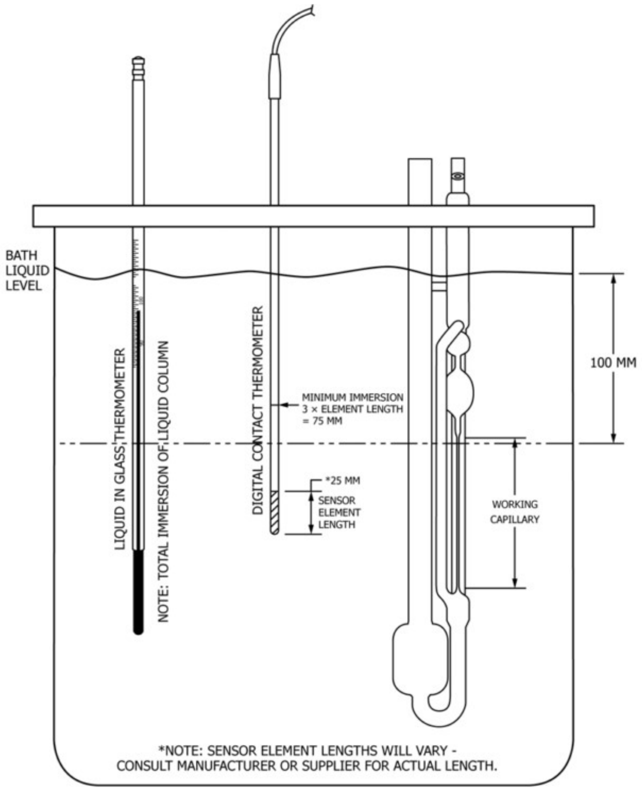


Figure 23 - Viscometer in Constant Temperature Bath (ASTM International, 2016)

Electron Microscopy

Due to the lack of particle counting equipment, a crude method was developed in the AFIT laboratory to make use of a scanning electron microscope. The researcher used the samples of 15W40 oil shown previously in Figure 24 which came from the 2011 Chevrolet 3500HD truck. In other words, they were sample codes D, E, and F. Additionally, a sample of large particles from the inner wall of the centrifuge rotor were scraped off with a small spatula and diluted with hexane in a test tube. All four hexane-diluted samples were left to settle overnight.

Figure 24 - Virgin, Filtered, and Used 15W40 Samples Diluted with Hexane

The following day, the samples were placed into an evaporator to off the volatile gasses to obtain a dry sample of particulates. After a few mildly successful attempts, a decision was made to attempt a cruder method of drawing the liquid volatiles off the sample by utilizing a filter media in a vacuum flask, shown in Figure 25. A major limitation here was the unavailability of preferred polycarbonate filters, so the researcher made due with glass microfiber filter paper, grade 691. The filters were designed for water chemistry use, but they achieved a decent performance. The filters were rated for

1.5-micron particle retention. Capturing the target range of 2-10-micron particles showed usable results.

Figure 25 - Flask and Vacuum Pump for Preparing Microscopy Samples

Once the particles were trapped on the filter media and dried, as shown in Figure 26, the paper was removed and sections were trimmed to fit on studs with double sided carbon tape then were ready to be placed on the microscope's viewing stage, as shown in Figure 27. The scanning electron microscope (SEM) was a Zeiss Evo model. Resulting images are shown and discussed in Chapter IV.

Figure 26 - Resulting Filter Media with Centrifuge Rotor Residual Particles

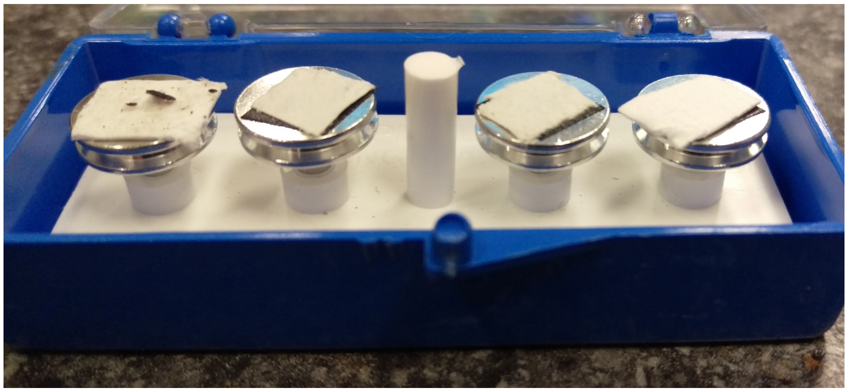


Figure 27 - Filter Media Sections Prepared with Carbon Tape on Microscope Studs

Summary

This chapter summarized the methodology used to determine, collect, and prepare samples of WMO for analysis. Procedures for filtering, testing fuel quality characteristics, and qualitatively analyzing particles were explained in detail. The results of these tests are shown and discussed in the next chapter.

IV. Results and Analysis

Overview of Results

The results from the tests mentioned in Chapter III were received from ALS Tribology and logged in a spreadsheet. The researcher was unable to carry out any inferential statistics due to the many differences in sample characteristics and small sample size. However, there was still an opportunity for descriptive statistics to investigate filtering effectiveness and to give ranges of possible contaminants as they apply to air pollution.

Overall, filtering with the centrifuge showed marginal results for how well it filtered out metals and in some cases, it surprisingly added metals to oil. In a couple cases where this effect was minor, it seemed easily attributable to testing error. In other cases, the cause was unknown and results were unexpected. Contamination may have not been fully flushed from the filtering system beforehand. A detailed look at filtering effectiveness is discussed later in the metals section. In addition, the differences between filtering methods is discussed next.

Filtering Method Comparison

To compare filtering methods, we can analyze are runs R, S and T. They highlight the difference between the centrifuge and the more traditional paper cartridge filters combined with a water separator. R was obtained from the bottom portion of a WMO collection barrel by using a pump and suction hose. This dirty sample was run through the centrifuge exactly like the other filtered samples. This gave us sample S. Furthermore, sample T was obtained by running the WMO through a four-filter series consisting of a water separator and paper and metal cartridges attached to the collection barrel which can be seen in Figure 18 in Chapter III.

Table 7 - Filtering Method Comparison for WMO Collection Barrel Sample

Name	*Fluid Description*		*Metals (ppm)*										*Contaminants (ppm)*		
	Condition	Method	Fe	Cr	Pb	Cu	Sn	Al	Ni	Ag	Ti	V	Si	Na	K
R	Used	----	89	4	20	33	2	11	1	<1	<1	<1	28	55	8
S	Filtered	Centrifuge	88	4	19	32	2	11	1	<1	<1	<1	28	56	9
T	Filtered	Cartridge	111	4	23	48	3	13	1	<1	<1	<1	32	66	10

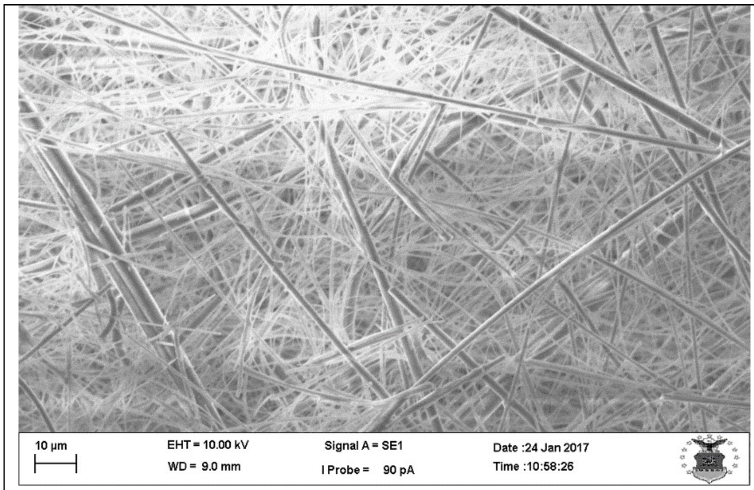
In every single metal species, the cartridge filter sample actually added more contaminants to the sample or remained the same instead of removing anything. The limitation to this experiment was that only one sample was gathered from the cartridge filter rig. It was known to the researcher that the filters in the rig were not new. They had previously been used to filter a few hundred gallons of WMO and diesel with sediment, so the filters were already saturated with metals. While realizing this was not a good assessment of the filter's potential effectiveness, the researcher did not waste an opportunity to send more samples to the tribology lab. Further research could be conducted for cartridge filters specifically, but it was not the intent of this study. It is seen that the centrifuge exhibits better cleaning qualities than the cartridge filters. Most cartridge type fuel filters are capable of filtering down to two microns while centrifuges are advertised by the manufacturer that they can achieve filtering effectiveness down to less than one micron (Fryer-to-Fuel, 2016).

Particulate Matter by Microscopy

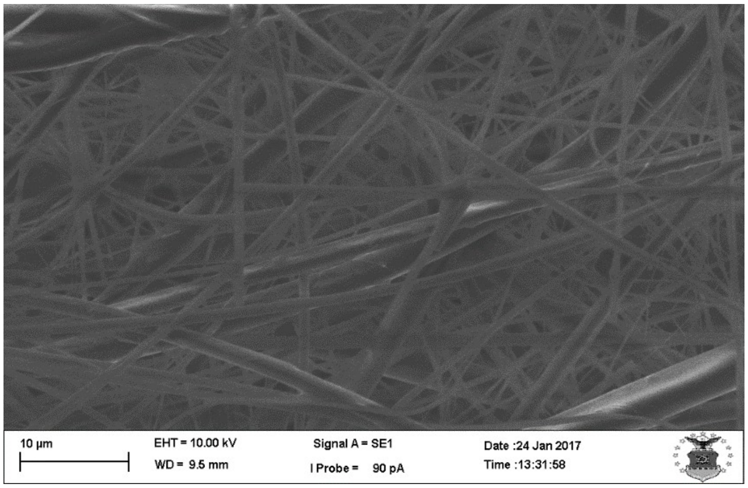
Without a proper sample preparation method and counting software, the researcher was unable to obtain concentration analyses, so a qualitative comparison approach was carried out using a Scanning Electron Microscope (SEM).

The particles found were suspected to be metal shavings, soot, carbon, and other engine related substances. It was impossible to distinguish what exactly each particle consisted of, but the particle size and concentration was more important anyway when considering wear on engine components, especially in the 2- to 10-micron range.

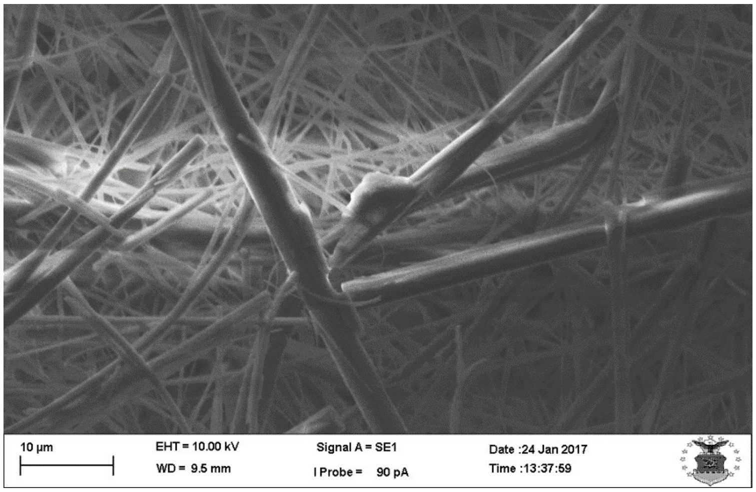
When viewing samples D, E, F, and the centrifuge rotor cap sludge, it was plainly seen there was an absence of particles in the virgin oil, sample D. The filter media, shown in Figure 28, contained particles ranging in size from 5- to 150-micron, but the concentration was scarce. The used motor oil, sample E, shown in Figure 29, contained particles ranging from 2- to 100-micron at a relatively high concentration. The centrifuge-filtered used oil, sample F, shown in Figure 30, contained particles ranging from 2- to 200-micron but had a visibly reduced concentration over the whole filter media as compared to sample E. The fourth sample viewed under the SEM was the centrifuge rotor cap sludge, shown in Figure 31, which had massive particles ranging from 2- to 2,000-micron with a very high concentration over the entire filter media. Obviously, this will not be introduced to any fuel blend. This concentration and size distribution was shown to visualize the types of contamination filtered out by the centrifuge. These particles are what need to be prevented from entering an engine's fuel system.



a. Fairly clean in most sectors of the filter media

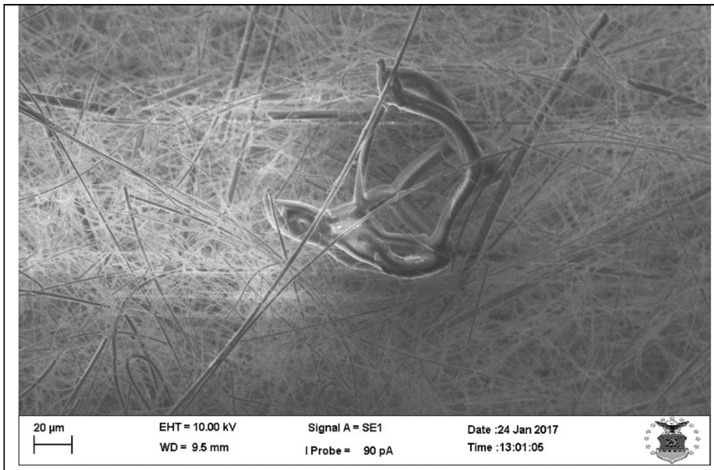


b. This sector is representative of the whole filter media. Very clean. No sign of small particles.

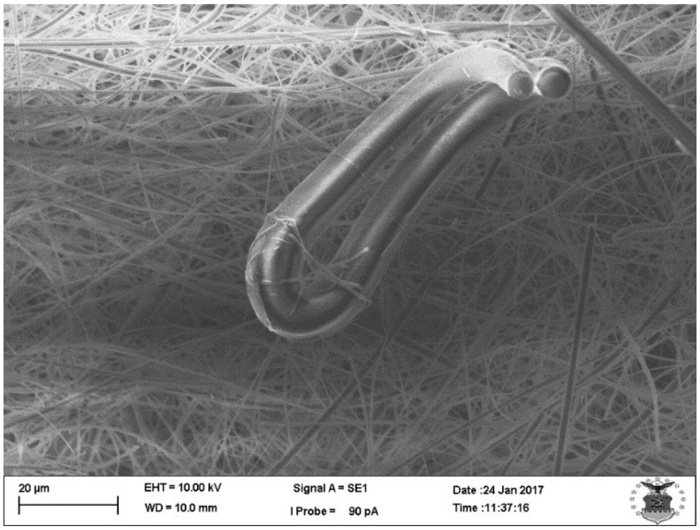


c. Small particles were rare and difficult to locate in this sample.

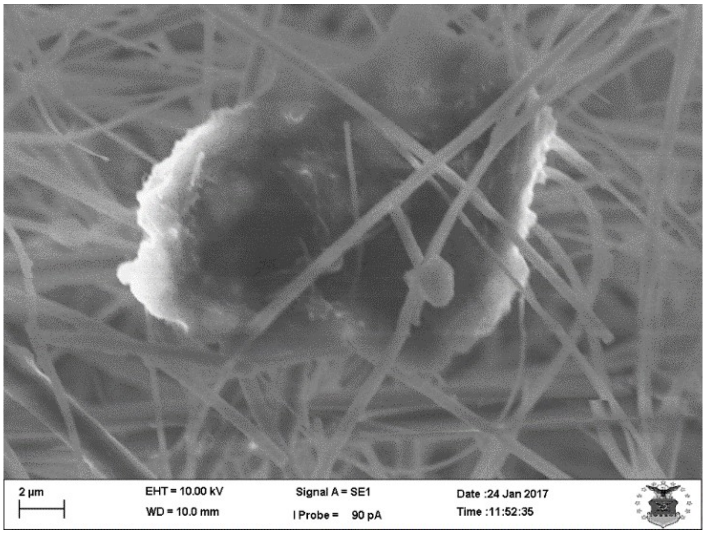
Figure 28 - Virgin 15W40 Motor Oil Viewed Under SEM



a. Possible metal shaving

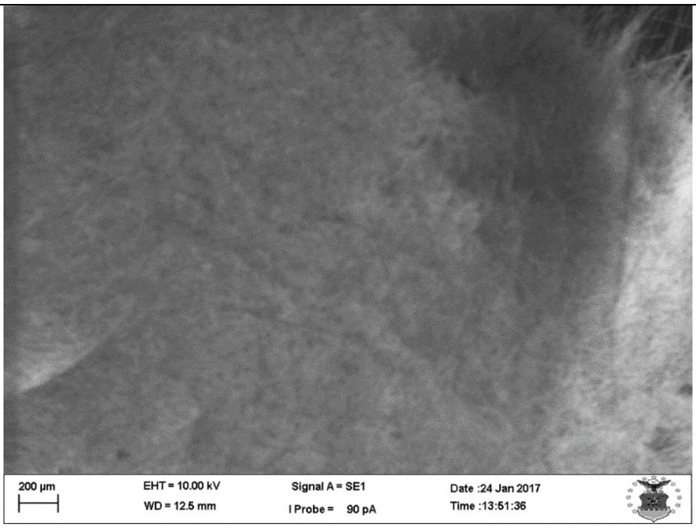


b. Possible metal shaving

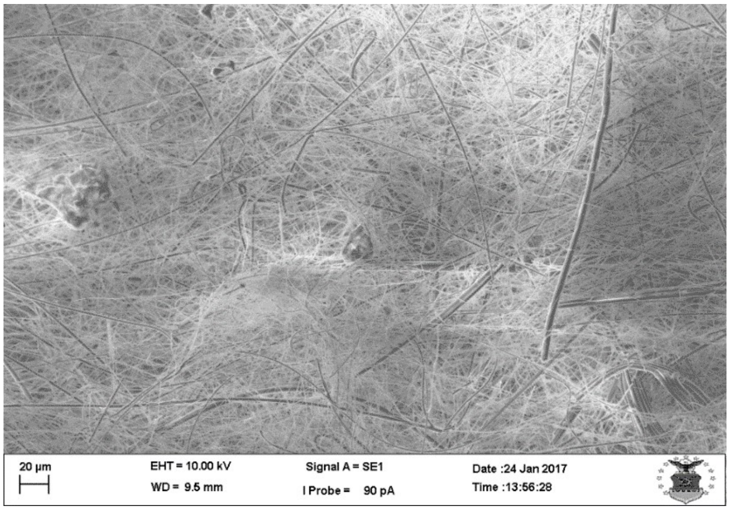


c. Edges were burning from electron beam

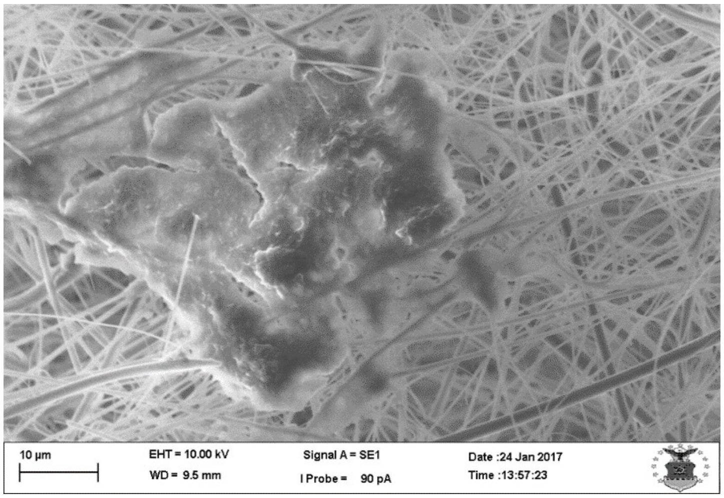
Figure 29 - Used 15W40 Motor Oil Viewed Under SEM



a. Void of larger particles in this sector of the filter media

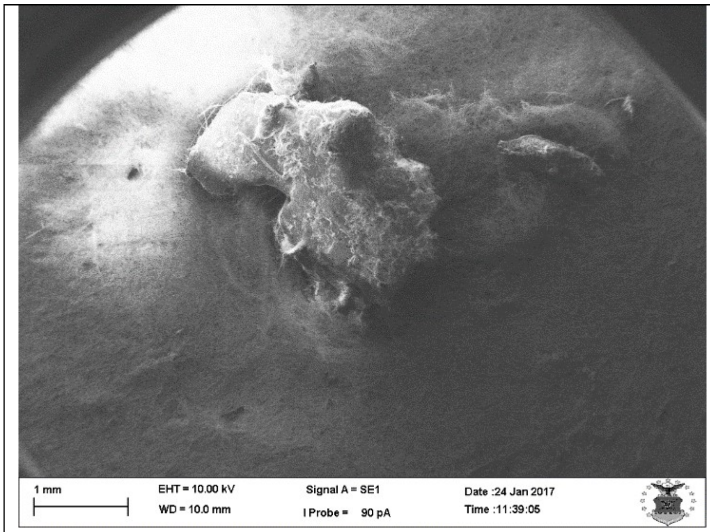


b. Shows scattering of medium to large particles throughout filter media

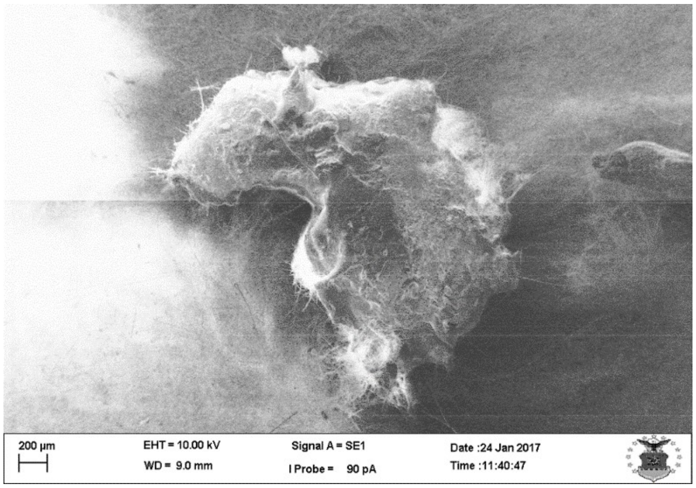


c. Electron beam was burning edges of particle, possibly soot from carbon.

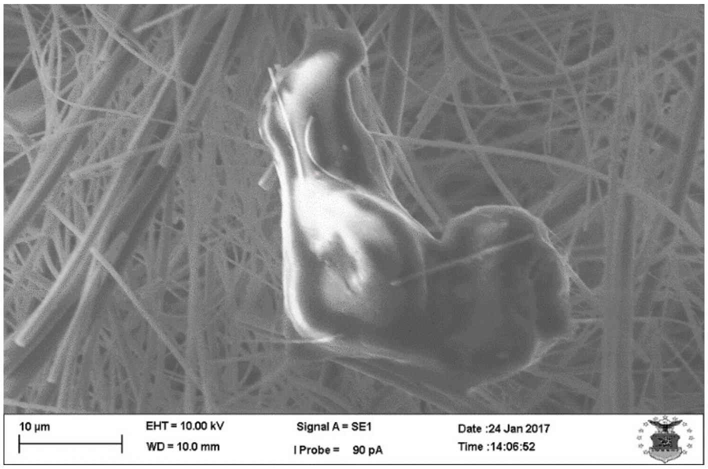
Figure 30 - Filtered 15W40 Motor Oil Viewed Under SEM



a. Very large particle 2mm long by 1mm wide.



b. Same particle from previous image zoomed in to show detail.



c. 20-micron particle representative of entire filter media.

Figure 31 - Centrifuge Rotor Cap Residual Particulate Matter Viewed Under SEM

Kinematic Viscosity

Figure 32 shows results from kinematic viscosity tests carried out by ALS Tribology at 100°C. The virgin oils were also tested for control. The virgin SAE 5W30 (sample C) was 63.1 cSt at 40°C and 10.4 cSt at 100°C. The virgin SAE 15W40 (sample D) was 110.4 cSt at 40°C and 15.1 cSt at 100°C. For comparison, two virgin diesel fuels were also tested, but only at 100°C. Diesel #2 (sample L) was 1 cSt and biodiesel (sample M) was 1.7 cSt.

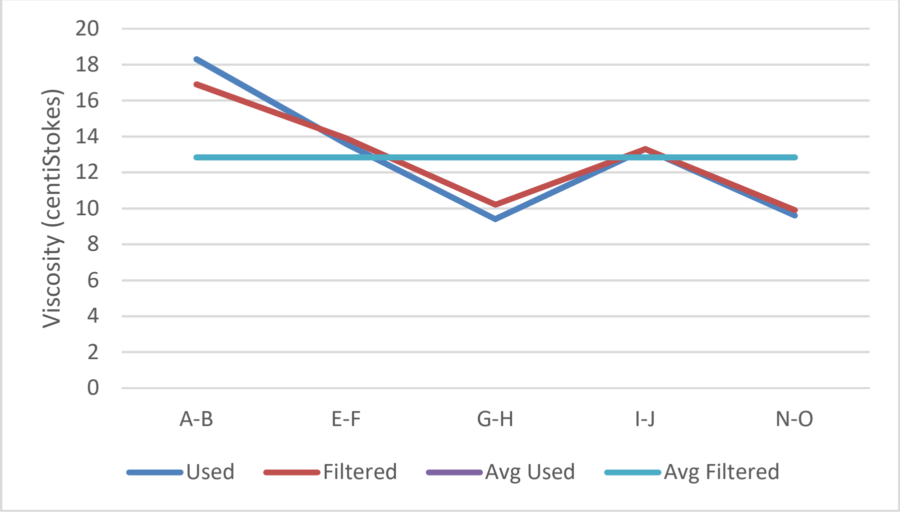


Figure 32 -Kinematic Viscosity of Paired WMO Samples at 100°C

Cummins specifies the viscosity of contingency diesel fuel should be 1.3-13.1 cSt at 40ºC (Cummins, 2017). Since the used and filtered oils were only tested at 100°C to represent the temperature of a running engine, viscosities were not very representative of ambient temperature that a diesel fuel blend would be stored at. To approximate a more useful comparison to diesel fuel, the oil viscosities can be estimated using a logarithmic regression to approximate a 40°C viscosity, but all published regression models are disputed and it is simpler to read a published viscosity vs. temperature curve, in this case for SAE 15W-40 from Viscopedia (Anton Paar GmbH, 2017). The filtered motor oil viscosity can be estimated between 90-120 centiStokes at 40°C by referencing a chart compiled by Viscopedia. Diesel fuel #2 was also provided by Viscopedia as 2.98 cSt measured at 40°C.

The following mixture equation can be used to predict a final blend viscosity:

$$v_{blend} = (B)(v_{WMO}) + (1 - B)(v_{diesel}), \tag{1}$$

where

v_{blend} = kinematic viscosity of resultant fuel blend, cSt

v_{WMO} = kinematic viscosity of WMO, cSt

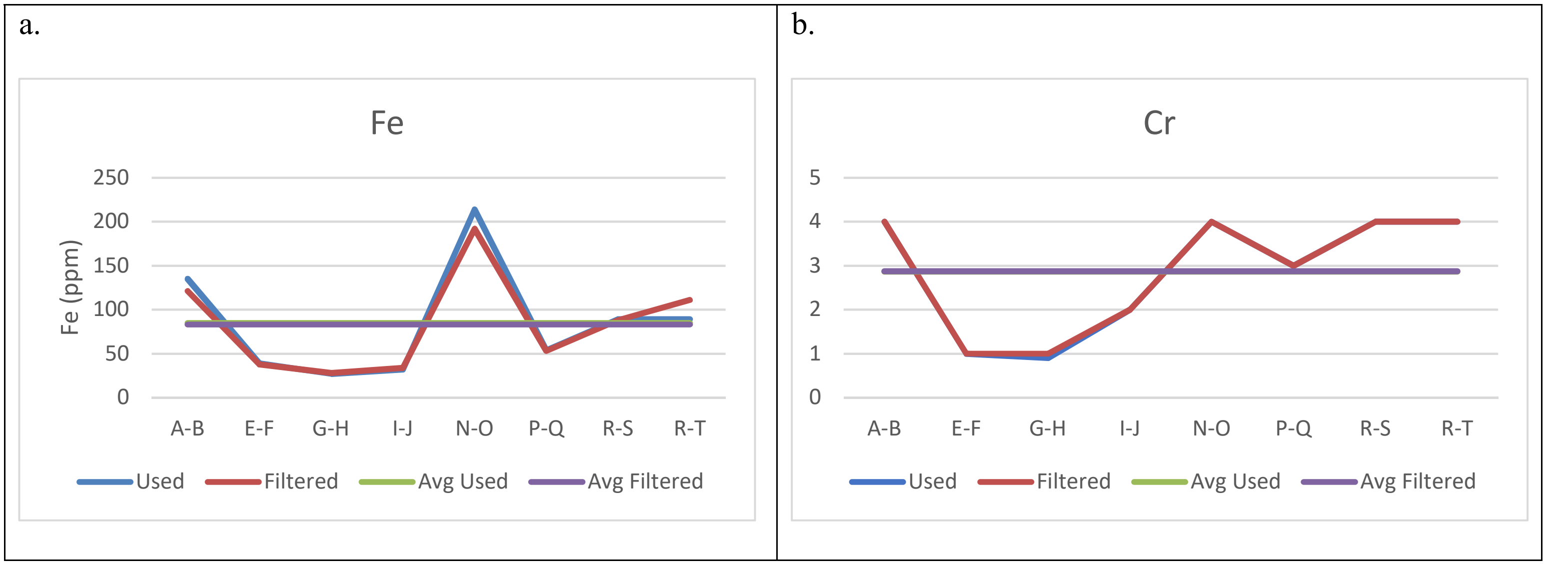
v_{diesel} = kinematic viscosity of diesel fuel, cSt

B = blend ratio of WMO to diesel fuel

If using a range of 90-120 cSt for oil and 2.98 cSt for diesel, both at 40°C, and a 5% WMO to diesel fuel blend, then the expected range of blended fuel viscosities should be 7.3-8.8 cSt at 40°C, above the range of tolerances for required diesel fuel, but within tolerances of the contingency diesel fuel specifications.

Metals

The spectrometry results from ALS Tribology showed metals concentrations for twenty metal species in each fluid sample. In many cases, filtering was only slightly effective at removing elemental metals if effective at all. Figure 33 over the next few pages shows the filter's effectiveness at mitigating metals concentrations. Each graph shows paired samples of used and filtered oils from the different donor vehicles. Note the difference in y-axis scales. Some elements had much larger concentrations than others. The difference between the first two lines in each graph shows the amount of material removed by filtration. In some cases, material was added by the filter. The next two lines are the average concentration of all samples for that species. In most species, the distinction between the average used concentration and the average filtered concentration is not distinguishable. In almost every metal species, sample pair R-T showed an increase. This sample pair was from the cartridge filter rig.



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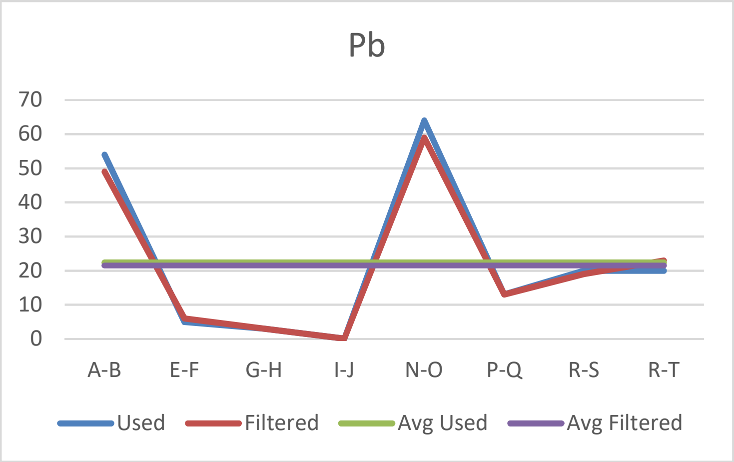
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20
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A-B
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I-J
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Avg Used
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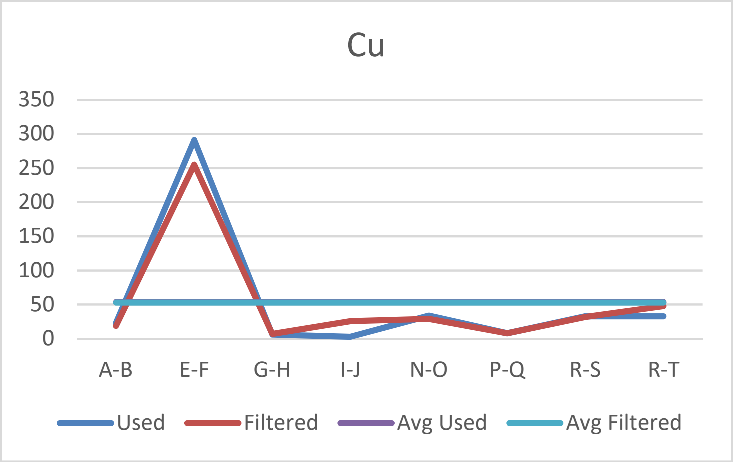
d.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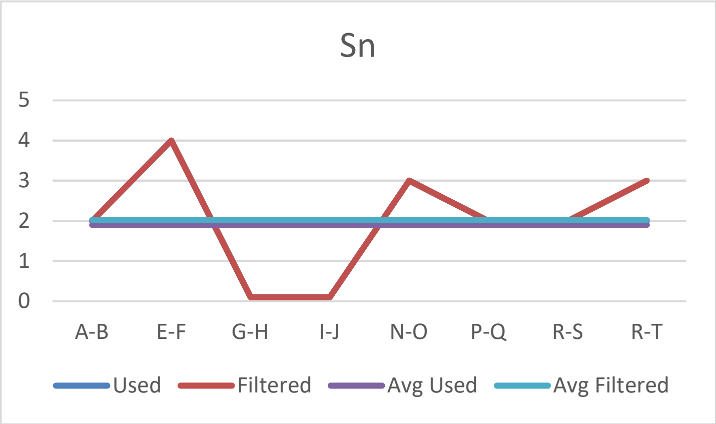
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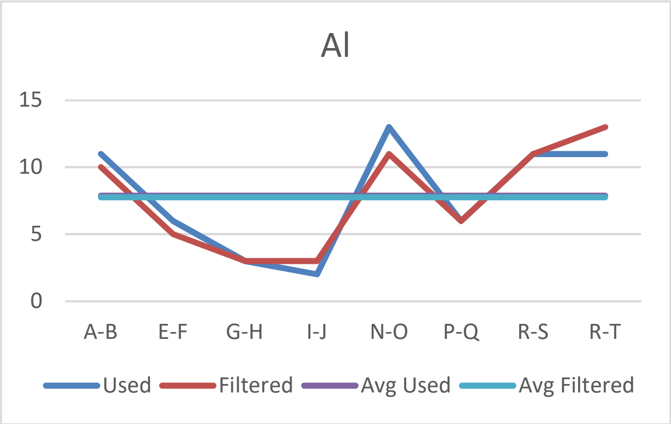
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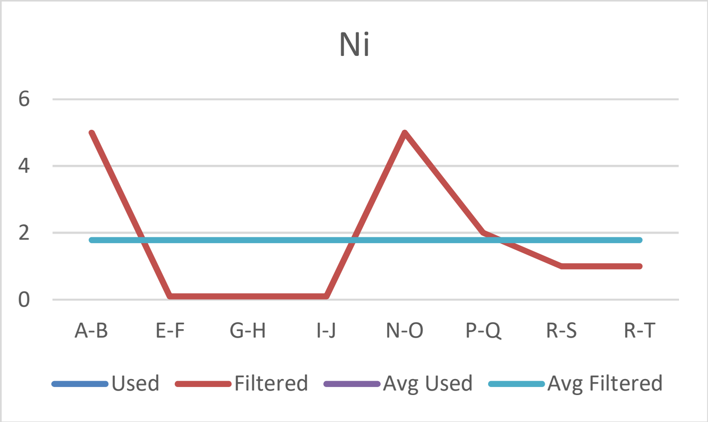
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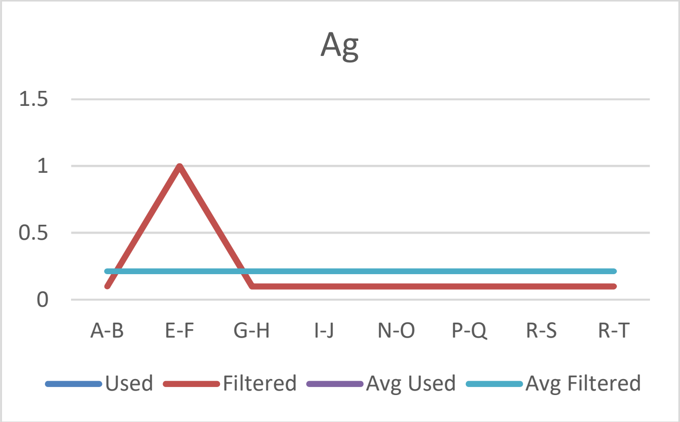
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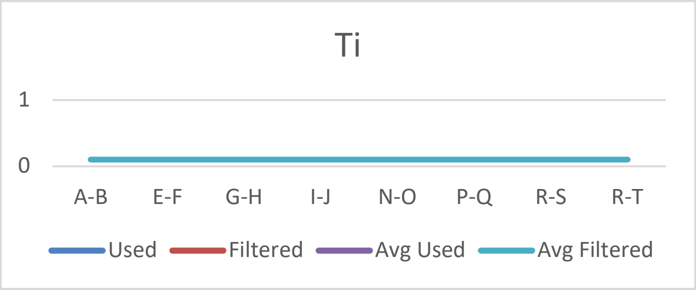
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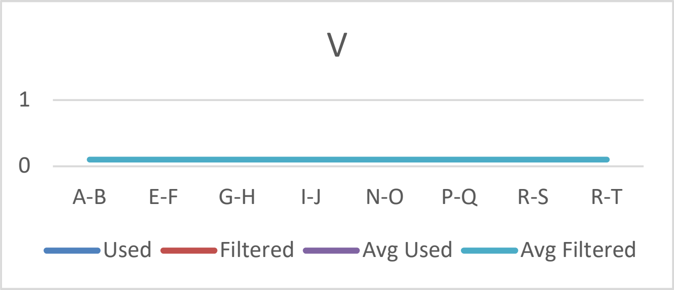
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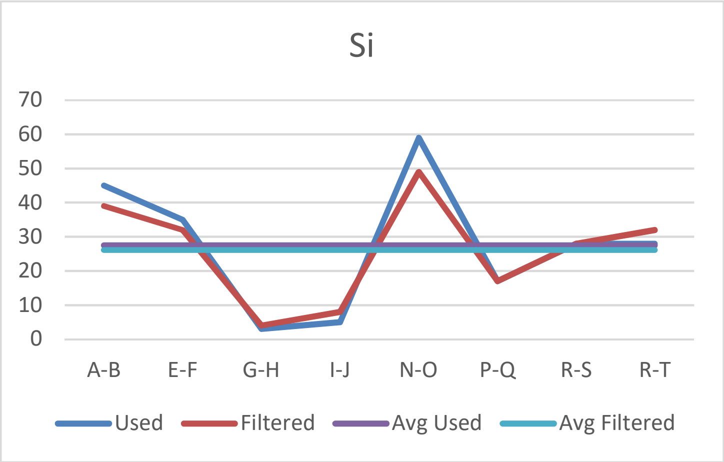
Si
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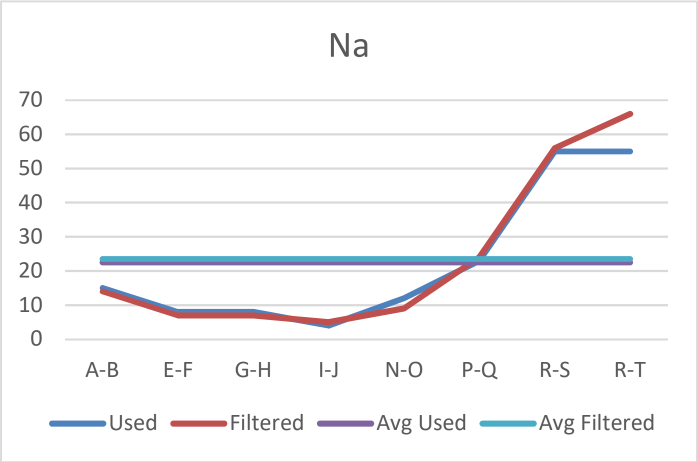
Avg Filtered

l.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60
50
40
30
20
10
0
A-B
E-F
G-H
I-J
N-O
P-Q
R-S
R-T
Used
Filtered
Avg Used
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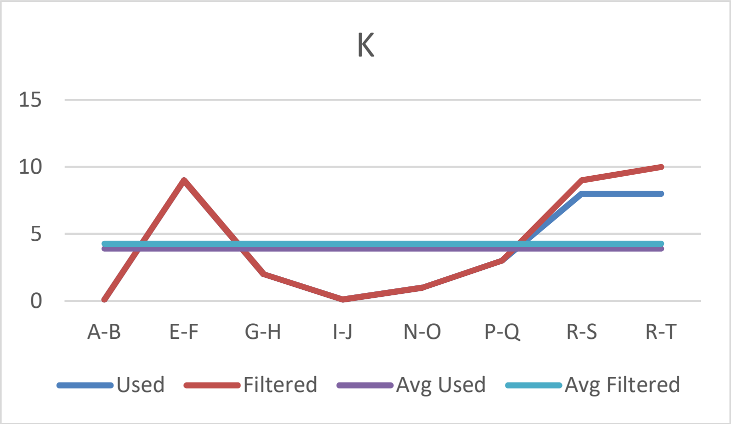
m.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10
5
0
A-B
E-F
G-H
I-J
N-O
P-Q
R-S
R-T
Used
Filtered
Avg Used
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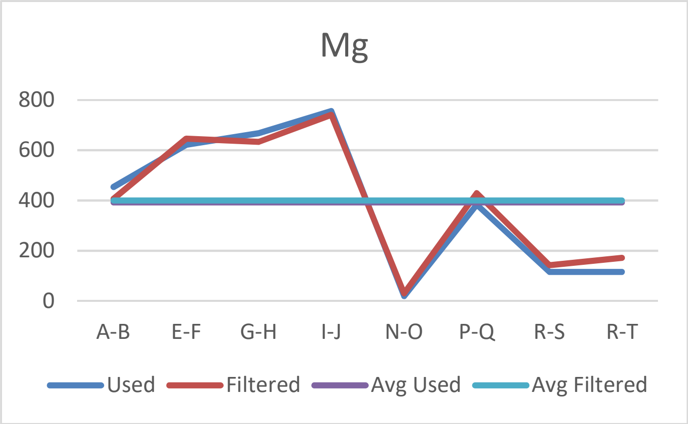
n.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P-Q
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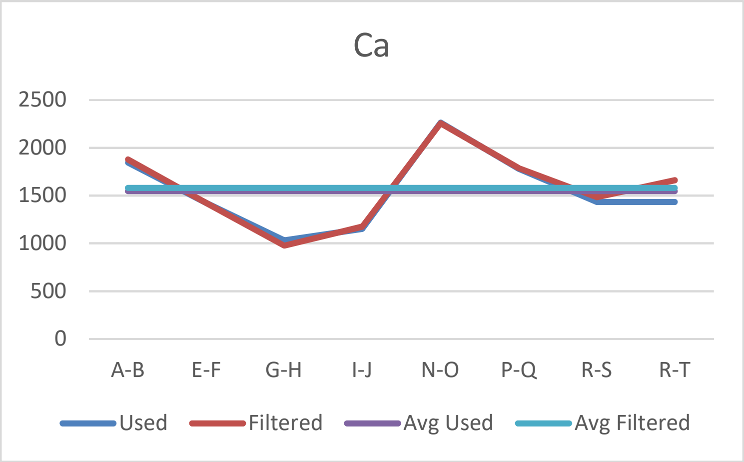
o.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1000
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0
A-B
E-F
G-H
I-J
N-O
P-Q
R-S
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Filtered
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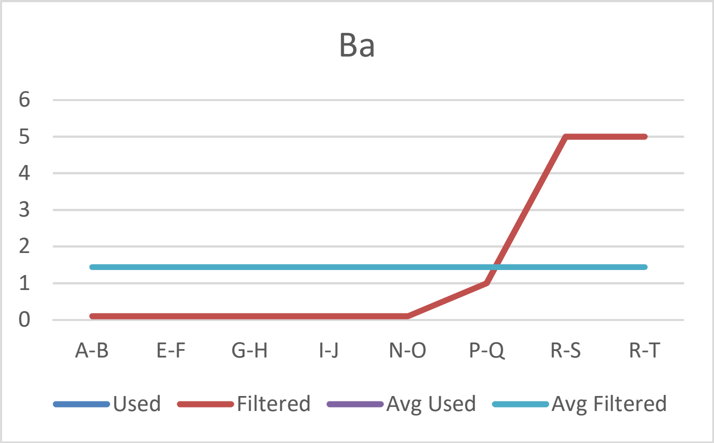
p.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3
2
1
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G-H
I-J
N-O
P-Q
R-S
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Filtered
Avg Used
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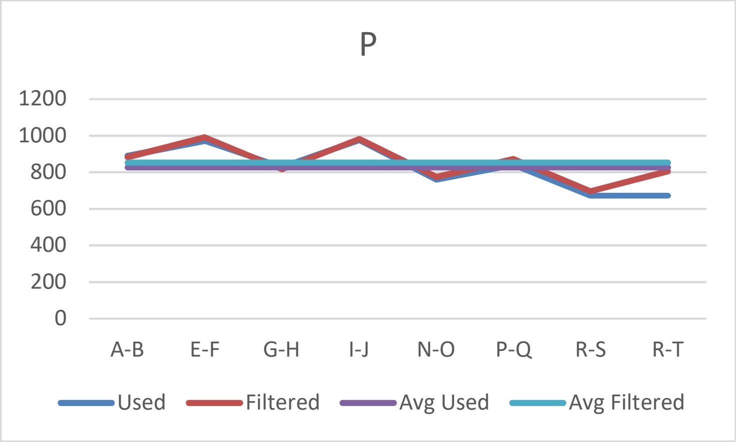
q.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200
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G-H
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N-O
P-Q
R-S
R-T
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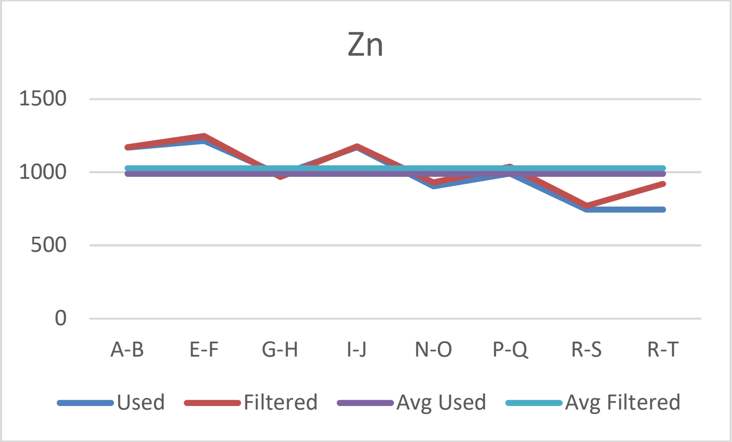
Filtered
Avg Used
Avg Filtered

r.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G-H
I-J
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R-S
R-T
Used
Filtered
Avg Used
Avg Filtered

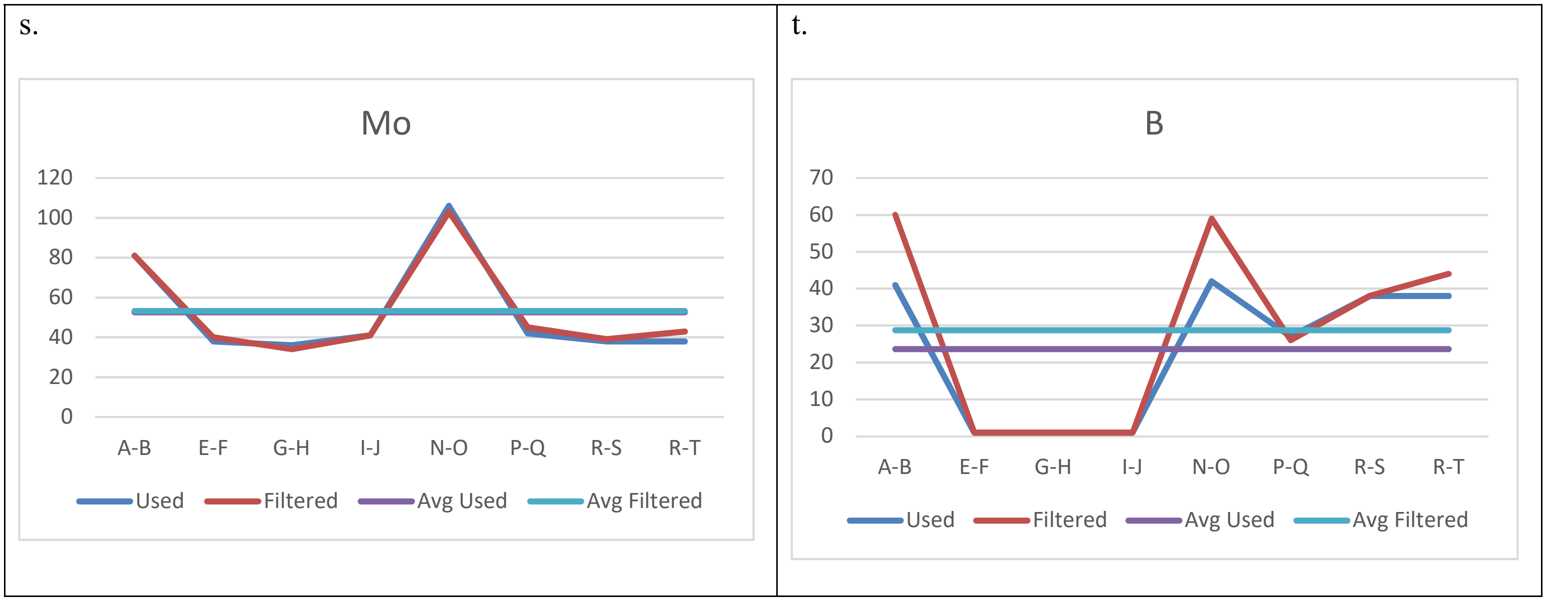

Figure 33 - Filtering Effectiveness on Metal Species

Focusing on only the samples filtered by the centrifuge, there were seven used samples that produced seven additional filtered samples. When the species concentrations of these fourteen samples are juxtaposed and arranged in descending order of concentration magnitudes, as shown in the next three figures, it can be seen that the amount removed by filtering is statistically insignificant. Upon closer inspection, there was no consistent removal rate, and in some cases the filtering method actually added contaminants instead of removing them.

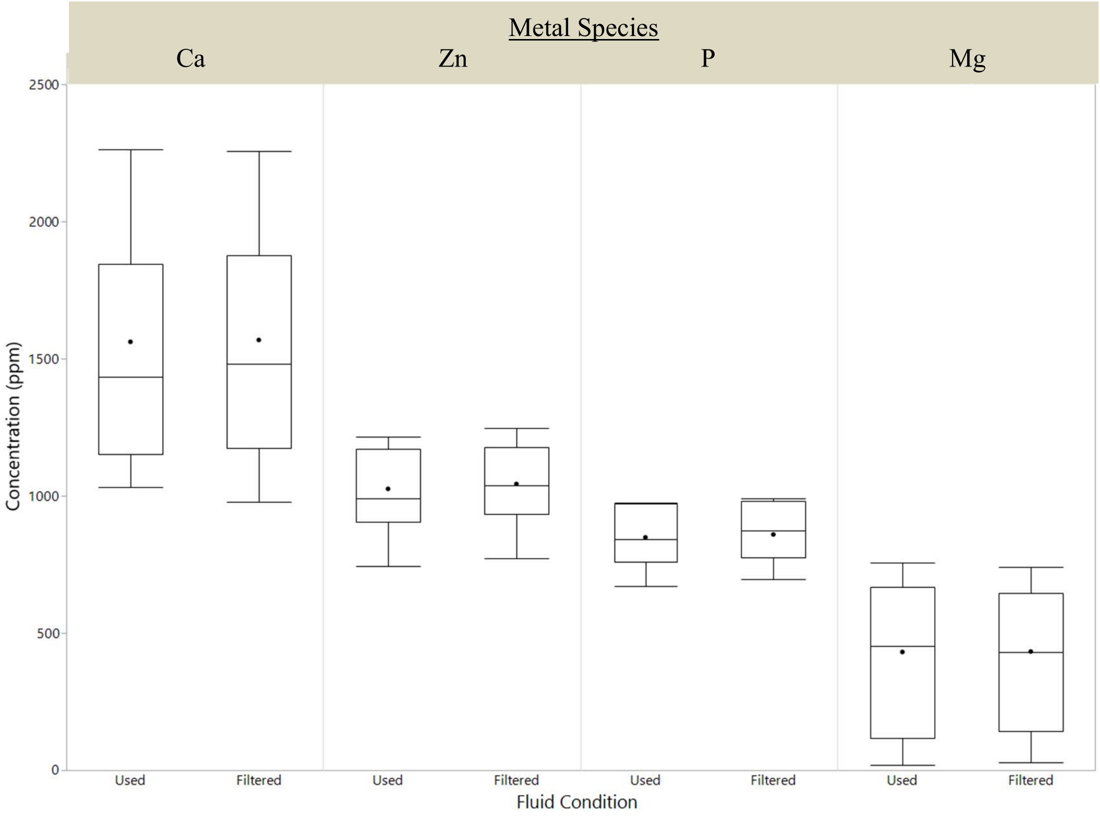

Figure 34 - Metals Filtering Comparison, Large Concentrations

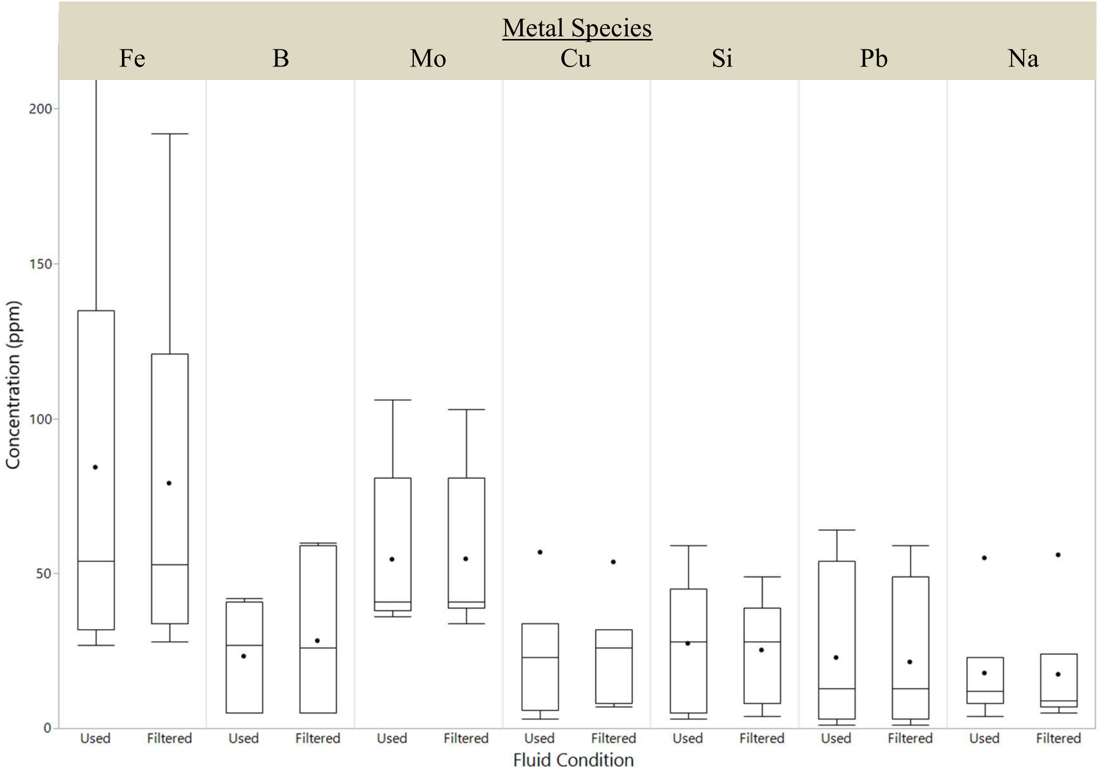

Figure 35 - Metals Filtering Comparison, Medium Concentrations

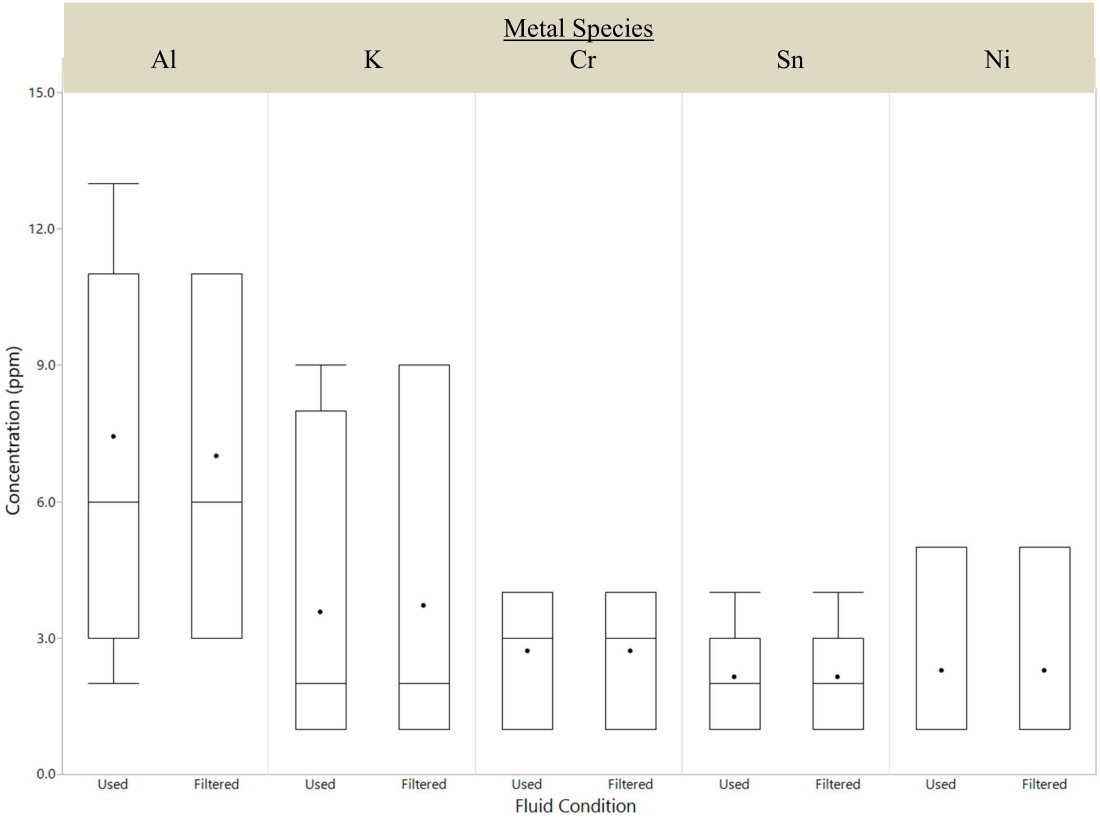

Figure 36 - Metals Filtering Comparison, Small Concentrations

There were eight species showing negative removal rates, meaning that material was added into the oil by the filtering process. In the case of the species with very low concentrations, this may have been an insignificant change at such a low concentration. For example, potassium (K) had a mean concentration of 3.3±3.1ppm in the seven dirty samples which were later filtered. This rose to 4.5±3.8ppm over seven filtered samples. This is such a small difference, but the percentage jump is relative to its magnitude.

Finally, to show if sodium, vanadium, aluminum, and silicon meet the required specifications for contingency diesel fuel prescribed in Table 3, the researcher took the worst-case metals concentration for each metal and blended it to 5% with diesel fuel. All diesel fuel samples contained <1ppm of each of the four metals. <1ppm is the reporting identifier for anything below the detection limits of the instrument. For math purposes, this was considered 1ppm. Therefore, using the maximum concentration of sodium found, 66ppm, Equation 1 was adapted to determine a blended concentration of 4.3ppm. The remaining blended concentrations were found as follows: 1.0ppm vanadium, 1.6ppm aluminum, and 3.4ppm silicon. Aluminum and silicon are both slightly above their maximum allowable thresholds, but keep in mind that these were worst case metals concentrations.

Water Content

Of twenty-three total samples, eighteen were free of water contamination, annotated as the lower detection limit of <0.05% on the tribology report. The remaining five samples, all obtained from the WMO collection barrel, contained trace amounts of water. The source of the water could have been from a maintenance issue with a donor vehicle's engine cooling system, such as a head gasket failure. If that was the case, tribology lab would also have detected coolant in the oil. The lab did test for coolant and all samples came back with negative results. Therefore, a better theory for the presence of water is that the WMO collection barrel had not been vented properly, trapping ambient air inside which could have condensed with temperature changes over time. The humidity of the air inside the barrel simply condensed droplets of water into the oil. This is one reason why collection barrels and tanks should be vented. Since petroleum products have a lower specific gravity than water and rise to the top of an aqueous solution, it would be expected that more water would be found in the bottom portion of the barrel. This was not the case. In fact, the lightest concentration of water was found in sample R, which was pulled from the bottom of the barrel. Sample R remained unfiltered. Another profound observation was with sample T, filtered with the forced cartridge method. This cartridge filter rig even included a water separator but did not seem to influence the water removal percentage. The centrifuge, however, which is not intended to de-water, did have a slight effect. Results of samples P, Q, R, S, and T from the WMO collection barrel can be seen in Table 8.

A major drawback to having water in these samples was the inability to carry out viscosity analyses. However, Cummins has declared in its contingency fuel specifications that absolutely nothing over 0.5% should be used. The preference is to keep water out completely. With any level of filtering in the test samples Q, S, and T, <0.5% was achieved, so the fuel is still considered safe by contingency standards. Keeping in mind, this level is targeted for undiluted diesel fuel, whereas a 5%WMO blend would render this water concentration to 0.000725% overall water in the generator's fuel supply, which is much less concerning and still below the required diesel fuel specification maximum of 0.05% volume-percent.

Table 8 - Water Contamination and Filter Effectiveness in WMO Barrel

Name	*Fluid Description*			*Contaminants*		*Filter Effectiveness*
	Condition	Barrel Strata	Filter Method	Coolant	Water (%)	Delta (±%)
P	Used	Top	----	No	0.52	
Q	Filtered	Top	Centrifuge	No	0.40	-23% removed water
R	Used	Bottom	----	No	0.34	
S	Filtered	Bottom	Centrifuge	No	0.41	+21% added water
T	Filtered	Bottom	Cartridge	No	0.35	+3% added water

Descriptive Statistics

Looking for reasons of filter effectiveness, the researcher tried a scatterplot of mean filter effectiveness versus the molecular weight of each element. Figure 37 shows this regression. As can be plainly seen, there is no correlation between filter effectiveness and the molecular weight of each element. Considering that the elements likely have formed into different compounds with different total molecular weights, this brief look tells the researcher that filter effectiveness is not linked to the elemental molecular weight of metals. Furthermore, without knowing which compounds these elements are formed into makes it impossible to further analyze filter effectiveness with this approach. The results from gas-chromatography (GC) might have shed more light on the chemical compounds present in the oil, but the level of fidelity in the GC analysis was so low, we must abandon this approach and accept the magnitudes of metals concentrations at face value.

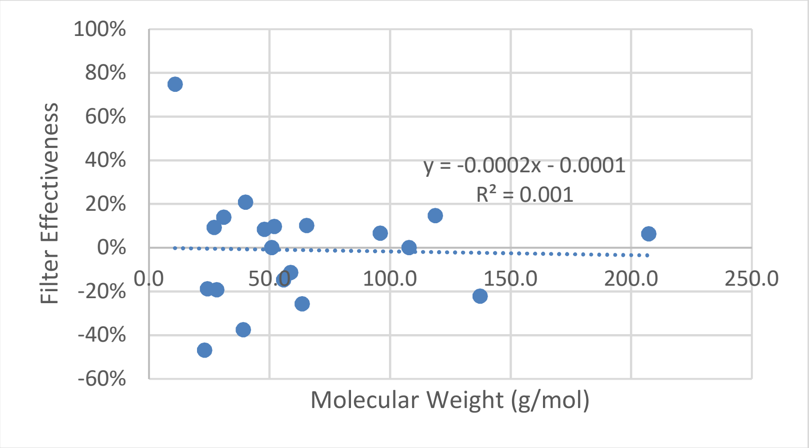

Figure 37 - Scatterplot of Molecular Weight vs Filter Effectiveness

Further descriptive statistics were carried out and place in Appendix B.

Chemical Characteristics

Gas-Chromatography (GC) results were poorly distinguishable due to high background noise. The instrument is designed with a resolution of parts per billion, whereas the samples in question were so dirty that they contained analytes in the parts per thousand. For perspective, average crude oil coming off a cracking tower has hundreds of thousands of components, so the background noise in a chromatograph such as this is understandable.

Qualitatively speaking, the chromatograph does show a distinct difference between a sample of virgin, used, and filtered oil from one vehicle. In this case, it was the 15W40 oil from the 2011 Chevrolet 3500HD Duramax: samples D, E, and F. The chromatograph is shown in Figure 38; the spike at 5 minutes represents the solvent, hexane.

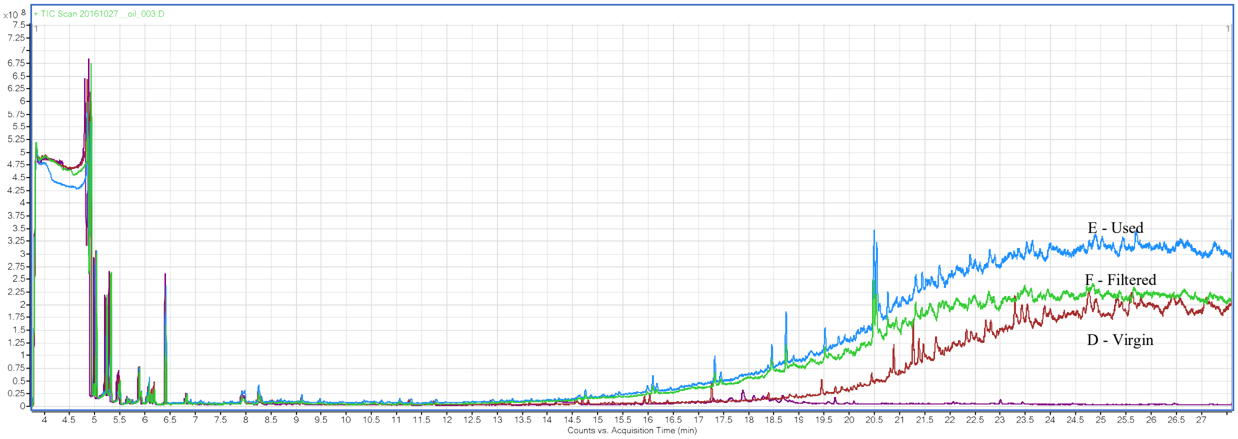

Figure 38 - Chromatograph of Chemical Differences in Motor Oil

Focusing on the latter half of the test, after 15 minutes, it is apparent the "cleanest" of the samples is the virgin oil which is represented by the bottom curve in the chromatograph, seen in Figure 39. The top curve, representing the used oil, has the highest abundance of compounds throughout, meaning it is the "dirtiest". The filtered oil curve follows a nearly identical shape curve and has similar peaks as the used oil curve above it, but the intensities of the peaks are reduced. This clearly shows that the centrifuge was effective in filtering out compounds. Had this been quantifiable, the previous discussion on molecular weight versus filter effectiveness could have been pursued further. There was no case where the filtered oil showed a higher abundance of compounds than the used oil sample. This analysis should not be compared to the previous analyses in this chapter for concentration of other contaminants such as metals. Chromatography looks at chemical characteristics only whereas spectrometry can show elemental metals.

Examining the virgin oil curve, it is evident that, for the most part, it has the same shape as the two curves above it. Aside from reduced intensity after 13 minutes, there is a slight phase shift of about 0.05 minutes, or 3 seconds. At first glance, a chemist should say this is a completely different substance, but since the shape fits so well except for the shift, it could be presumed that the lighter weight of the clean virgin oil allowed it to travel through the column faster than the dirty oils that followed it. In addition to the weight-affected cleanliness of the oil, it was also impossible for the researcher to determine if the virgin motor oil was exactly the same manufacturer and brand as the used sample taken from the truck's crankcase. Since government contracts sometimes rotate through different oil distributors for multiple reasons, 88LRS could not confirm what oil it had used for the vehicle in question. Therefore, a bold but necessary assumption was made that the collected virgin motor oil was of the same manufacturer and brand as was used in the truck before the dirty sample was collected at the maintenance interval.

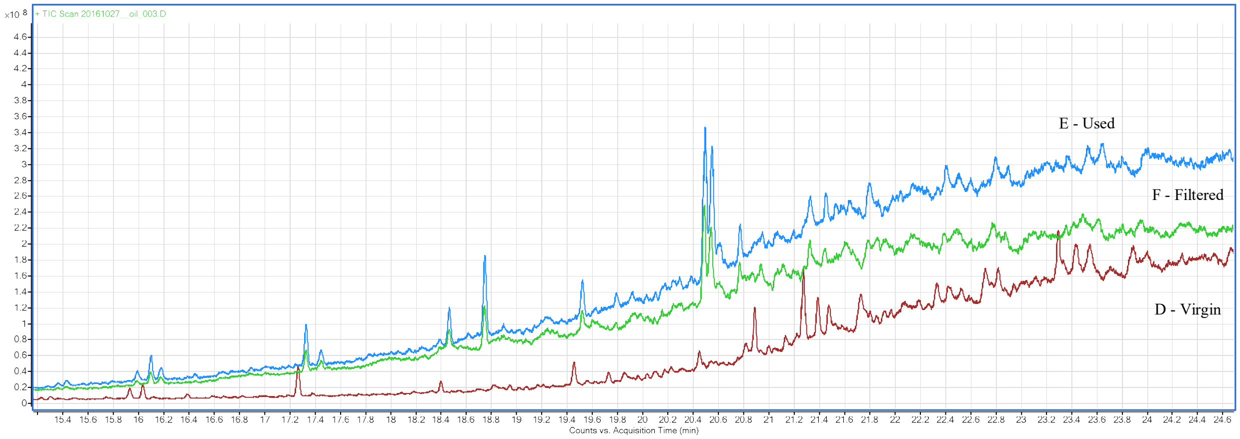

Figure 39 - Chromatograph Rescaled to Highlight Differences

When looking closer using the mass spectrometry National Institute of Standards and Technology (NIST) Library within Mass Hunter software, many compounds were associated with the major peaks. It was impossible to determine which characteristics defined what the compounds could have been. When the peaks were subtracted, other heavy aliphatic compounds were seen coming through. However, several potential peak compounds were as top contenders. Table 9 below shows possible compounds at selected major peaks could have represented similar characteristics. These results should be taken very critically because there so much background noise in this test that it was impossible to determine any compounds with even a moderate level of confidence.

Table 9 - Possible Compounds Determined by Mass-Spectrometry

Peak Time (min)	*Compound*
17.33	tetrapentacontane
17.45	hexadecenoic acid
18.46	tetrapentacontane
18.74	hexadecanoic acid, methyl ester
19.52	hexadecenoic acid
20.49	methyl ester
20.55	hexadecenoic acid

Air Pollution Considerations

Gaussian Model

To determine the environmental impact that WMO contributes to the air from burning toxic heavy metals, we can apply the metals concentrations in the liquid oil to a Gaussian dispersion model (Cooper & Alley, 2011; Masters & Ela, 2008). This will give us a metals concentration in air so we can compare to published Permissible Exposure Levels (PEL) from agencies such as OSHA, ACGIH, and WEEL.

$$C = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right)\left\{exp\left(-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^2}\right) + exp\left(-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^2}\right)\right\} \quad (2)$$

where

C = steady-state concentration at a point (x,y,z), mg/m^3

Q = emissions rate, mg/s

σ_y,σ_z = horizontal and vertical spread parameters, m

(these are functions of distance, x, and atmospheric stability)

u = average wind speed

y = horizontal distance from plume centerline, m

z = vertical distance from ground level, m

H = effective stack height, m

(H=h+Δh, where h=physical stack height and Δh = plume rise)

We must make some assumptions for this to be feasible. First, the engine is running at steady state. Second, the metals pass through in complete combustion, ignoring effects of blowby. Third, the engine has a straight pipe exhaust so we can ignore SCR, DPF, and EGR effects. Fourth, we will assume motor oil has the same density as diesel fuel. This is outright false, but at such a low blend rate, the effects of density are negligible. A simple dilution model can be embedded in the blend ratio, adapted from Equation 1 used in the kinematic viscosity analysis section, but the densities of the WMO samples have a wide range. The fifth assumption we need to make is that the exhaust is at ground level and there are no obstructions between the exhaust and observer. Finally, for weather conditions, we will choose average weather conditions with a wind speed of 2m/s on an unstable day ("stability condition B" in *Air Pollution Control* textbook; Table 20.1 in Appendix C) (Cooper & Alley, 2011).

With these bold assumptions, Equation 2 simplifies to give us a timed average concentration of our metal species so we can compare to PELs.

$$C = \frac{Q}{\pi u \sigma_y \sigma_z}, \quad (3)$$

We are given a metals concentration, in ppm, from the tribology lab results. To model a worst-case scenario, the highest concentration was chosen from each species, but it was divided between used and filtered oils to see if there is a noticeable difference. We also know the density of diesel fuel, 0.832 kg/L and can choose an oil-to-fuel blend ratio. In this study, we were given a 5% maximum threshold by Cummins, but we can choose anything between 0-100% to see titration effects on the concentrations as compared to the

PEL. Finally, we know the fuel consumption rate of the engine from the Cummins QSK38 specifications shown below in Table 10 (Cummins, 2009).

Table 10 - Cummins QSK38 Fuel Consumption @1800RPM (60Hz) (Cummins, 2009)

%	kWm	BHP	L/hr	US gal/hr
Standby Power				
100	1279	1715	315	83.3
Prime Power				
100	1063	1425	262	69.3
75	797	1069	202	53.4
50	532	713	153	40.3
25	265	356	90	23.7
Continuous Power				
100	891	1195	223	59.0

Sample Calculation

We start by choosing the worst-case scenario. At 100% standby power, we use 315 L/hr. Multiplying this by the density of diesel fuel, the engine is burning 263 kg/hr.

Then we choose the highest concentration of iron in the tested WMO samples, 214 mg/kg, then blend it with diesel fuel to 5%, giving us a concentration of iron in fuel of 10.7 mg/kg. Next, to find the emission rate of the contaminated fuel, Q, we multiply the metal concentration by the flow rate of fuel and convert hours to seconds, giving us a metal emission rate of 0.78 mg/s.

To calculate the horizontal and vertical spread parameters, we choose from a few options on a stability classification table and a subsequent table of curve-fit constants in *Air Pollution Control* (Cooper & Alley, 2011) as can be seen in Appendix C.

$$\sigma_y = ax^b = 156x^{0.894}$$

$$\sigma_z = cx^d + f = 106.6x^{1.149} + 3.3$$

where x is distance from source, km

Assuming the generator operator is standing 2 meters away, or 0.002km, the parameters reduce to σ_y=0.6m and σ_z=3.4m.

Now we have all the parameters to complete the Gaussian model and we calculate an average concentration, C, of 0.061 mg/m3 at the operator. Comparing that to the OSHA 8-hour average PEL table, the iron oxide value is limited at 10 mg/m3. According to this, we can burn WMO at a 5% without exceeding that level. Refer to Table 11 for the remainder of the results. The same results are better visualized in Figures 40 and 41.

Exposure Levels Comparison

The researcher created an Excel spreadsheet to calculate the levels of all metals in oil. The spreadsheet was separated into two tabs, one for only the filtered oil samples and one for dirty unfiltered samples to see the magnitude of difference between each. There was only a slight difference when the oil-to-fuel blend was turned up to 100%. The researcher could postulate that filtering is unnecessary to mitigate emissions hazards from burning while also assuming the emissions control devices on an engine will capture most of the harmful metals. However, there are other reasons why filtering should remain in place, namely to prevent damage to the engine’s fuel system from the abrasion of these metal particles.

Table 11 - Comparison of Results to Permissible Exposure Levels

Compare to OSHA Table Z-1 (8-hr PEL)		**Metals Emission (5% Fuel Blend)**	
Substance	PEL mg/m^3	Dirty WMO	Filtered WMO
Iron oxide	10	0.061	0.055
Chromium metal and insoluble salts	1	0.004	0.001
Chromium (II) compounds	0.5		
Chromium (III) compounds	0.5		
Lead inorganic (see 1910.1025)	0.05	0.025	0.017
Tetraethyl lead	0.075		
Tetramethyl lead	0.075		
Copper fume	0.1	0.083	0.072
Copper dusts and mists	1		
Tin, as inorganic compounds (except oxides)	2	0.003	0.001
Tin, as organic compounds	0.1		
Aluminum metal - total dust	15	0.009	0.004
Aluminum metal - respirable fraction	5		
Nickel carbonyl	0.007	0.001	0.001
Nickel, metal and insoluble compounds	1		
Silver, metal and insoluble compounds	0.01	0.000	0.000
Titanium dioxide - total dust	15	0.001	0.000
Ferrovanadium dust	1	0.000	0.000
Respirable dust	0.5		
Silicon - total dust	15	0.017	0.014
Silicon - respirable fraction	5		
Sodium fluoroacetate	0.05	0.016	0.019
Sodium hydroxide	2		
Magnesium oxide fume - total particulate	15	0.215	0.183
Calcium silicate - total dust	15	1.836	0.641
Calcium silicate - respirable fraction	5		
Barium, soluble compounds	0.5	0.001	0.001
Barium sulfate - total dust	15		
Barium sulfate - respirable fraction	5		
Phosphoric acid	1	0.635	0.281
Zinc chloride fume	1	0.719	0.354
Zinc oxide fume	5		
Zinc oxide - total dust	15		
Zinc oxide - respirable fraction	5		
Molybdenum - soluble compounds	5	0.040	0.029
Molybdenum - insoluble compounds - total dust	15		
Molybdenum - insoluble compounds	3		
Boron oxide - total dust	15	0.137	0.017
Boron trifluoride	3		

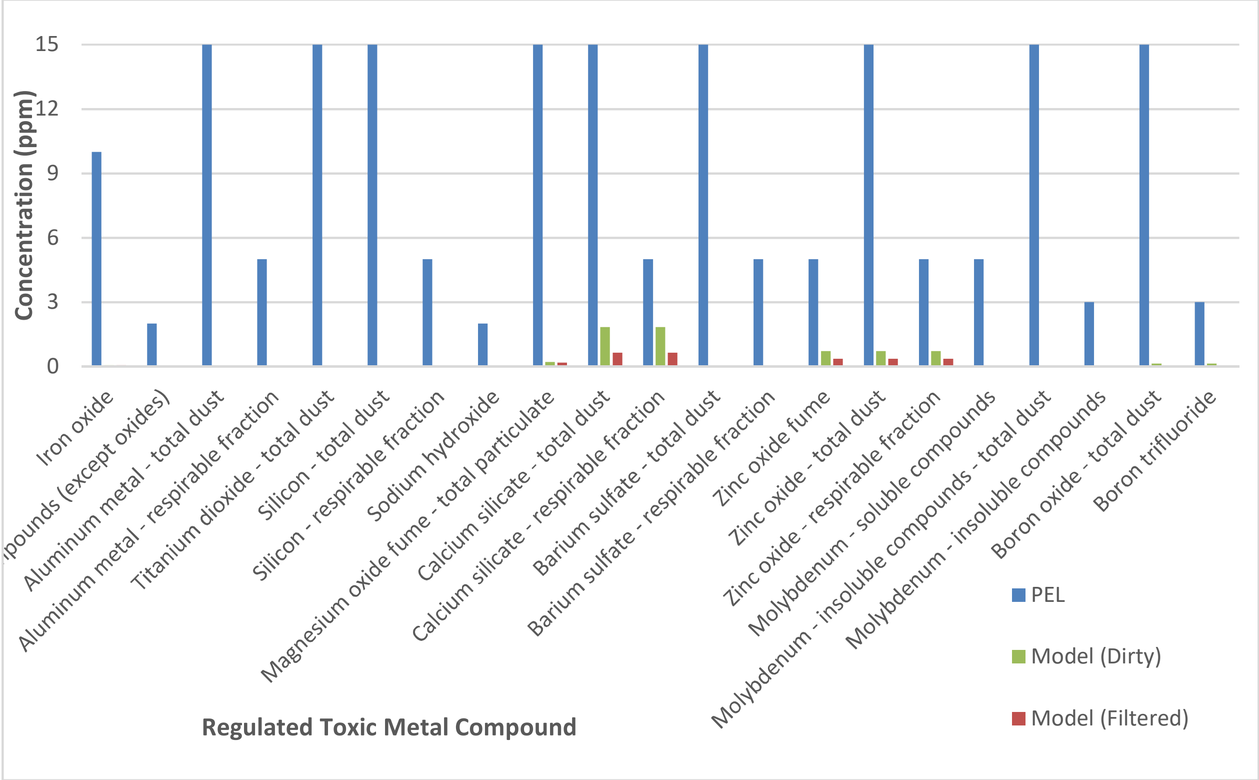

Figure 40 - Permissible Exposure Level Comparison, ≤15ppm

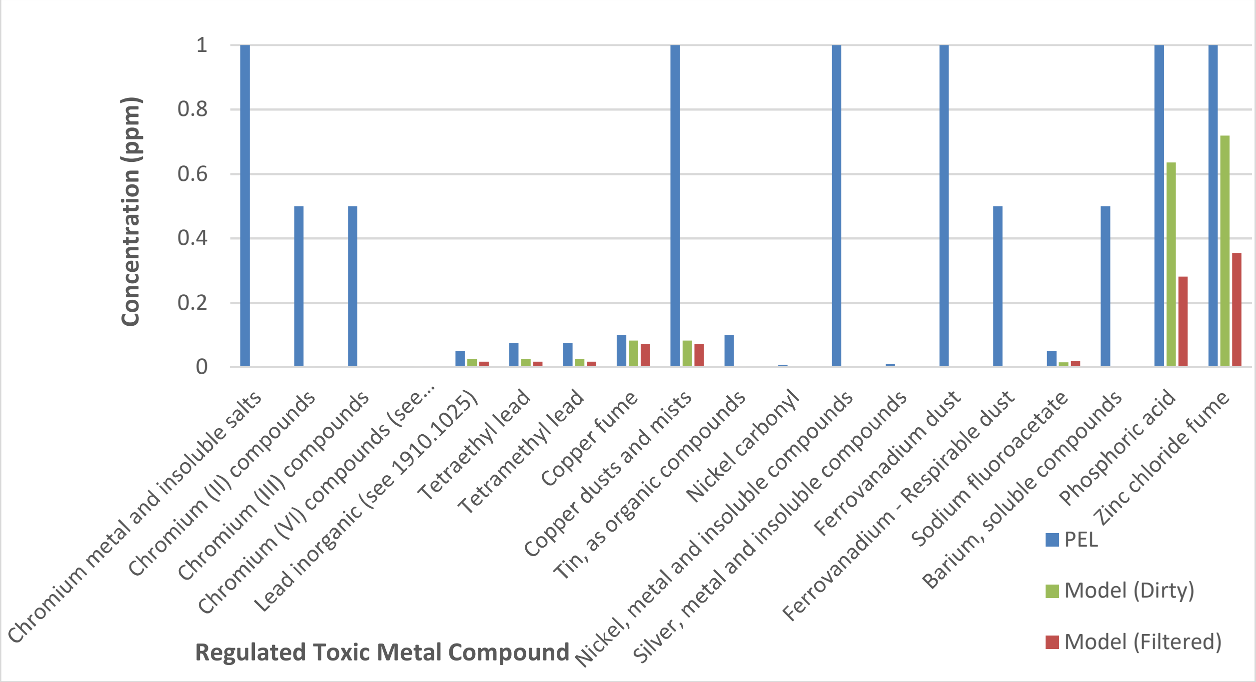

Figure 41 - Permissible Exposure Level Comparison, ≤1ppm

Summary

In summary, the results from comparing filtering methods, analyzing particulate matter with microscopy, kinematic viscosity, metals, water and coolant, and chemical characteristics with GC were discussed. Air pollution considerations were calculated based on a Guassian dispersion model and the results were compared to a permissible exposure limit table and visualized in column charts.

V. Discussion

Summary of Research

In summary, the researcher has studied metals, viscosity, water content, and other topics related to using WMO as an alternative supplemental fuel source. While the data was erratic for filter effectiveness, it did not rule out burning WMO as an alternative recycling method. This considers the assumption of blend concentrations remaining under 5% and the emissions control devices on the BPU handling most of the exhaust emissions. At 5%, the WMO is diluted with diesel fuel so much that the metal concentrations are rendered trivial which allows exhaust emission levels to remain below permissible exposure levels without the assistance of stock engine emissions control devices. The results relevant to diesel fuel specifications are shown below in Table 12.

Table 12 - Comparison of Research Results to Fuel Requirements (Cummins, 2017)

	Required Diesel Fuel (2017)[1]	**Contingency Diesel Fuel (2017)[2]**	**5% WMO Blend**
Kinematic Viscosity	1.3 to 4.1 cSt at 40°C	1.3 to 13.1	7.3 to 8.8
Sodium Content	0.5ppm maximum	10ppm	4ppm
Water & Sediment	Not to exceed 0.05 volume-percent	0.5 volume-percent	0.07 volume-percent
Carbon Residue	Not to exceed 0.35 mass-percent on 10 volume-percent residuum	5.0 mass-percent	0.1 mass-percent
Density	0.816-0.876 g/cc at 15°C	0.750-0.965	0.822-0.846
Heavy Metals		Vanadium 5ppm max Aluminum 1ppm max Silicon 1ppm max	1ppm 2ppm 3ppm

[1] Ultra Low Sulfur Diesel – Required in all highway diesel vehicles as of 2006.

[2] Additional maintenance may be required when using contingency fuels.

Based on information from Cummins, Inc's experience on the matter, the BPU is expected to perform with negligible diminished power output while using up to a 5% WMO-fuel blend. No permanent damage to the fuel system is expected at such a low fuel blend ratio, however, there is anticipated attrition of fuel filters, coking of injector nozzles, clogging of the catalyst, and potential scarring of the high-pressure fuel pump. Knowing that modern diesel engine fuel delivery systems can handle WMO blends at a low ratio, the research questions posed in Chapter I can now be answered:

- How much filtration is required for WMO to be considered clean enough for use?
    - Based on Cummins filtration research, filtering to 5-micron is permissible, but 2-micron is better. Coincidentally, these are the sizes of the two-stage factory filters installed on the BPU. If WMO is not filtered whatsoever, a more rapid attrition of filter cartridges is expected.
- What harmful environmental effects exist?
    - There is the potential for increased levels of metals emissions into the air which can cause occupational health risks to anyone working near a BPU in operation. In this study, theoretical exhaust emissions from a 5% fuel blend did not exceed OSHA PEL, as determined by the Gaussian dispersion model. However, these levels would need to be confirmed with direct measurement techniques.

Significance of Research

The significance of this research impacts DoD energy supply and security. It can be applied at contingency bases of all sizes and mission sets. The ability to burn alternative fuels in diesel generators extends the fuel supply and mitigates the burden of handling hazardous waste removal at contingency bases when the focus should be on the combat missions deployed forward from these bases.

Recommendations for Action

It is recommended to develop a simple and easy WMO collection routine to bring the WMO from the maintenance shops to the generator fuel supply locations. The WMO can be filtered on site and introduced into the fuel tank immediately. Once the WMO is blended with the fuel, it is no longer treated as hazardous waste. Civil Engineer craftsmen possess the in-house capability of constructing a simple filter rig with commercial-off-the-shelf fuel filtering components. If cartridge filters are used, they should be arranged in sequence with descending micron ratings, with the recommended levels starting at 10-micron and descending to 2-micron. An additional recommendation to improve performance awareness is to install a pressure gauge before each filter. A sudden drop in pressure before a filter shows that filter is clogged and needs to be replaced immediately.

If a centrifuge is used, commercial-off-the-shelf products exist catering to fuel blending hobbyists. These suppliers make kits of hardware that will fit on a 55-gallon drum; however, many are customizable and relatively inexpensive. A barrel of oil should be allowed to continuously cycle through the centrifuge for multiple passes before dumping into a fuel tank. A single pass through the centrifuge may not remove enough containments. It is advisable to follow the manufacturer's recommendation no matter what filter setup is used.

Finally, if there is any doubt that a WMO barrel may have water or coolant in it, the barrel should be rejected and disposed of through traditional hazardous waste procedures instead of attempting to de-water. There is very low reward compared to the risk of unnecessarily introducing water to any fuel system.

Recommendations for Future Research

Addressing the limitations to this study is a great start to furthering research in this method of recycling. In this study, the oil samples were unable to be followed from virgin source to waste product, so the virgin samples used were not an exact comparison to the waste products studied. To further explore engine component wear, particle size and concentration should be obtained from more virgin and waste motor oil samples. In addition, a partnership with the diesel engine manufacturer would be greatly beneficial.

Once the component wear has been sufficiently studied, a look at changes in exhaust emissions from different WMO fuel blends would be necessary to influence the decision on whether this WMO recycling method is beneficial.

Empirical testing of exhaust emissions would be beneficial as well, to determine the consequences relating to occupational health risks.

Finally, both economic and environmental life cycle analyses should be performed to compare this research to traditional WMO disposal and recycling methods.

Appendix A: Sample Information

The following four tables in Appendix A display the raw data given by ALS Global Tribology Lab and the categories of model and usage information for the different sample donor vehicles involved in this study.

UnitName	Fluid Description			Compartment Condition		Metals (ppm)									
	Condition	Filter Method	Weight	Severity	Problem Code	Fe	Cr	Pb	Cu	Sn	Al	Ni	Ag	Ti	V
Deuce	Used		15W40	Normal		15	1	2	2	<1	3	<1	<1	<1	<1
Chevy	Used		15W40	Normal		17	<1	<1	3	<1	4	<1	<1	<1	<1
Bobber	Used		15W40	Severe	Wear	147	13	89	45	11	31	2	<1	2	<1
A	Used		5W30	Abnormal	Low ipH	135	4	54	23	2	11	5	<1	<1	<1
B	Filtered	Centrifuge	5W30	Abnormal	Oil	121	4	49	19	2	10	5	<1	<1	<1
C	Virgin - Motor Oil		5W30	Normal		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
D	Virgin - Motor Oil		15W40	Normal		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
E	Used		15W40	Normal		39	1	5	291	4	6	<1	1	<1	<1
F	Filtered	Centrifuge	15W40	Normal		38	1	6	255	4	5	<1	1	<1	<1
G	Used		15W40	Severe	Fuel	27	<1	3	6	<1	3	<1	<1	<1	<1
H	Filtered	Centrifuge	15W40	Abnormal	Fuel	28	1	3	7	<1	3	<1	<1	<1	<1
I	Used		15W40	Normal		32	2	<1	3	<1	2	<1	<1	<1	<1
J	Filtered	Centrifuge	15W40	Normal		34	2	<1	26	<1	3	<1	<1	<1	<1
L	Virgin - Diesel		D2	Normal		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
M	Virgin - Biodiesel		B20	Normal		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
N	Used		5W30	Abnormal	Oil	214	4	64	34	3	13	5	<1	<1	<1
O	Filtered	Centrifuge	5W30	Caution	Dirt	192	4	59	29	3	11	5	<1	<1	<1
P	Used		various	Abnormal	Water	54	3	13	8	2	6	2	<1	<1	<1
Q	Filtered	Centrifuge	various	Caution	Water	53	3	13	8	2	6	2	<1	<1	<1
R	Used		various	Caution	Oil	89	4	20	33	2	11	1	<1	<1	<1
S	Filtered	Centrifuge	various	Caution	Water	88	4	19	32	2	11	1	<1	<1	<1
T	Filtered	Cartridge	various	Caution	Water	111	4	23	48	3	13	1	<1	<1	<1
U	Used		ATF	Normal		28	<1	2	16	<1	4	<1	<1	<1	<1

Unit Name	Fluid Description			Contaminants (ppm)			Additives (ppm)						
	Condition	Filter Method	Weight	Si	Na	K	Mg	Ca	Ba	P	Zn	Mo	B
Deuce	Used		15W40	5	10	<5	38	2371	<1	1161	1233	4	42
Chevy	Used		15W40	11	4	<1	459	2101	<1	1318	1626	98	483
Bobber	Used		15W40	28	34	4	182	6467	<1	2237	2532	142	196
A	Used		5W30	45	15	<1	453	1845	<1	890	1169	81	41
B	Filtered	Centrifuge	5W30	39	14	<1	407	1878	<1	882	1172	81	60
C	Virgin - Motor Oil		5W30	3	8	<1	10	2276	<1	803	1004	82	252
D	Virgin - Motor Oil		15W40	4	3	<1	921	1078	<1	1057	1296	63	<5
E	Used		15W40	35	8	9	622	1422	<1	971	1214	38	<5
F	Filtered	Centrifuge	15W40	32	7	9	646	1422	<1	991	1248	40	<5
G	Used		15W40	3	8	2	668	1032	<1	829	984	36	<5
H	Filtered	Centrifuge	15W40	4	7	2	633	977	<1	816	967	34	<5
I	Used		15W40	5	4	<1	756	1153	<1	976	1171	41	<5
J	Filtered	Centrifuge	15W40	8	5	<1	741	1174	<1	982	1177	41	<5
L	Virgin - Diesel		D2	<1	<1	<1	<1	<1	<1	<1	<1	<1	<5
M	Virgin - Biodiesel		B20	<1	<1	<1	<1	<1	<1	<1	<1	<1	<5
N	Used		5W30	59	12	1	19	2263	<1	761	904	106	42
O	Filtered	Centrifuge	5W30	49	9	1	30	2256	<1	775	932	103	59
P	Used		various	17	23	3	384	1782	1	841	992	42	27
Q	Filtered	Centrifuge	various	17	24	3	429	1788	1	873	1037	45	26
R	Used		various	28	55	8	116	1433	5	672	745	38	38
S	Filtered	Centrifuge	various	28	56	9	142	1482	5	696	771	39	38
T	Filtered	Cartridge	various	32	66	10	172	1662	5	805	919	43	44
U	Used		ATF	5	3	<1	6	89	4	231	15	<1	90

Unit Name	Fluid Description		Contaminants		Physical Tests						Physical/Chemical	
					Viscosity							
	Condition	Weight	Water (%)	Coolant	40°C (cSt)	100°C (cSt)	Fuel (%)	Solids (%)	PQ Index	Soot (%) Infrared	TBN (mgKOH/g)	TAN (mgKOH/g)
Deuce	Used	15W40	<0.05	No		15.5	<1			<0.1	7.7	
Chevy	Used	15W40	<0.05	No		15.0	<1			0.3	5.5	
Bobber	Used	15W40	<0.05	No		15.2	<1			0.8	6.4	
A	Used	5W30	<0.05	No		18.3			<10		1.2	
B	Filtered -Centrifuge	5W30	<0.05	No		16.9			<10		1.7	
C	Virgin - Motor Oil	5W30	<0.05		63.1	10.4		<0.1	<10			1.76
D	Virgin - Motor Oil	15W40	<0.05		110.4	15.1		<0.1	<10			2.04
E	Used	15W40	<0.05	No		13.6	<1		<10	0.3	4.2	
F	Filtered - Centrifuge	15W40	<0.05	No		13.9	<1		<10	0.3	4.4	
G	Used	15W40	<0.05	No		9.4	6		<10	<0.1	2.1	
H	Filtered - Centrifuge	15W40	<0.05	No		10.2	5		<10	<0.1	2.6	
I	Used	15W40	<0.05	No		13.3	<1		<10	<0.1	5.8	
J	Filtered - Centrifuge	15W40	<0.05	No		13.3	<1		<10	<0.1	5.7	
L	Virgin - Diesel	D2	<0.05	No		1			<10	<0.1	<1.0	
M	Virgin - Biodiesel	B20	<0.05	No		1.7			<10	<0.1	<1.0	
N	Used	5W30	<0.05	No		9.6			<10		<1.0	
O	Filtered - Centrifuge	5W30	<0.05	No		9.9			<10		1.3	
P	Used	various	0.52	No		N/A			<10		4.2	
Q	Filtered - Centrifuge	various	0.40	No		N/A			<10		4.4	
R	Used	various	0.34	No		N/A			<10		2.2	
S	Filtered - Centrifuge	various	0.41	No		N/A			<10		2.4	
T	Filtered - Cartridge	various	0.35	No		N/A			<10		2.8	
U	Used	ATF	<0.05			7.7		0.1	<10			0.96

UnitName	Other info	Date Collected	Date Filtered	Date Reported	Unit Make Name	Unit Model	Year of Manufacture	Compartment Make Name	Compartment Model Name	Compartment Type	Fluid Manufacturer	Fluid Name	Fluid Grade	Time on Unit	Comp't Age (mi)	Comp't Age (hrs)	Time on Fluid	Customer Number	Company Name
Deuce		13-Feb-11		23-Mar-11	Kaiser-Jeep	M35A2	1970	Continental	LDT-465	Diesel Engine	Shell	Rotella T	SAE 15W40	32443	32443		443	251373	Zach Bierhaus
Chevy				9-Dec-16	Chevrolet	2500HD	2005	Duramax	LLY	Diesel Engine	Delo	400 LE	SAE 15W40	327128	327128	5537	9755	251373	Zach Bierhaus
Bobber		27-Nov-16		12-Dec-16	Kaiser-Jeep	M35A2	1971	White	LDT-465	Diesel Engine	unknown	unknown	unknown	41924	41924	465	unknown	251373	Zach Bierhaus
A	Used	9-Sep-16		19-Dec-16	Chevrolet	3500	2003	Vortec	6000	Gas Engine	Lyden	ProGuard ECO	SAE 5W30	50959	50959		unknown	251375	AFIT
B	Filtered - Centrifuge		12-Oct-16	19-Dec-16	Chevrolet	3500	2003	Vortec	6000	Gas Engine	Lyden	ProGuard ECO	SAE 5W30	50959	50959		unknown	251375	AFIT
C	Virgin - 5W30	9-Sep-16		16-Dec-16							Lyden	ProGuard ECO	SAE 5W30				unknown	251375	AFIT
D	Virgin - 15W40	5-Oct-16		16-Dec-16							Lyden	ProGuard HD CJ-4	SAE 15W40				unknown	251375	AFIT
E	Used	5-Oct-16		16-Dec-16	Chevrolet	3500HD	2011	Duramax	LMM	Diesel Engine	Lyden	ProGuard HD CJ-4	SAE 15W40	11962	11962		unknown	251375	AFIT
F	Filtered - Centrifuge		12-Oct-16	16-Dec-16	Chevrolet	3500HD	2011	Duramax	LMM	Diesel Engine	Lyden	ProGuard HD CJ-5	SAE 15W40	11962	11962		unknown	251375	AFIT
G	Used	5-Oct-16		20-Dec-16	International	Bucket Truck	2005	Navistar	DT466	Diesel Engine	Lyden	ProGuard HD CJ-6	SAE 15W40	40180	40180	5803	unknown	251375	AFIT
H	Filtered - Centrifuge		12-Oct-16	20-Dec-16	International	Bucket Truck	2005	Navistar	DT466	Diesel Engine	Lyden	ProGuard HD CJ-7	SAE 15W40	40180	40180	5803	unknown	251375	AFIT
I	Used	5-Oct-16		15-Dec-16	Ford	F350	2012	Ford	Powerstroke	Diesel Engine	Lyden	ProGuard HD CJ-8	SAE 15W40	11001	11001		unknown	251375	AFIT
J	Filtered - Centrifuge		12-Oct-16	15-Dec-16	Ford	F350	2012	Ford	Powerstroke	Diesel Engine	Lyden	ProGuard HD CJ-9	SAE 15W40	11001	11001		unknown	251375	AFIT
L	Virgin - Fuel	4-Nov-16		19-Dec-16								Diesel Fuel	No. 2					251375	AFIT
M	Virgin - Fuel	4-Nov-16		16-Dec-16								Biodiesel	B20					251375	AFIT
N	Used	4-Nov-16		19-Dec-16	Chevrolet	3500 Van	2003	Vortec	6000	Gas Engine	Lyden	ProGuard ECO	SAE 5W30	52294	52294		unknown	251375	AFIT
O	Filtered - Centrifuge		8-Nov-16	16-Dec-16	Chevrolet	3500 Van	2003	Vortec	6000	Gas Engine	Lyden	ProGuard ECO	SAE 5W30	52294	52294		unknown	251375	AFIT
P	Used	4-Dec-16		19-Dec-16	various	various	various	WMO Barrel	Top	various	various	motor oil	various		unknown		unknown	251375	AFIT
Q	Filtered - Centrifuge		6-Dec-16	19-Dec-16	various	various	various	WMO Barrel	Top	various	various	motor oil	various		unknown		unknown	251375	AFIT
R	Used	4-Dec-16		19-Dec-16	various	various	various	WMO Barrel	Bottom	various	various	motor oil	various		unknown		unknown	251375	AFIT
S	Filtered - Centrifuge		6-Dec-16	19-Dec-16	various	various	various	WMO Barrel	Bottom	various	various	motor oil	various		unknown		unknown	251375	AFIT
T	Filtered - Cartridge		4-Dec-16	19-Dec-16	various	various	various	WMO Barrel	Bottom	various	various	motor oil	various		unknown		unknown	251375	AFIT
U	Used ATF	5-Dec-16		17-Dec-16	Chevrolet	2500HD	2005	Suncoast (2001)	GMAX 5	Auto Transmission	Valvoline	ATF	DEX/MERC	328024	19717	unknown	19717	251375	AFIT

Appendix B: Descriptive Statistics

The following four tables in Appendix B show descriptive statistics calculated by the researcher from data reported by ALS Tribology in December 2016.

Parameter	*Waste Oils**						
	N	min-max	median	mean	±St Dev	variance	CV%
Fe (ppm)	11	15-147	39	72.5	62.7	7.9	87%
Cr	11	<1-13	2	3.2	3.4	1.8	105%
Pb	11	<1-89	5	23.1	29.7	5.4	128%
Cu	11	2-291	16	42.2	79.9	8.9	190%
Sn	11	<1-11	2	2.6	2.8	1.7	106%
Al	11	2-31	6	8.5	7.9	2.8	93%
Ni	11	<1-5	1	1.9	1.5	1.2	79%
Ag	11	<1-1	1	1.0	0.0	0.0	0%
Ti	11	<1-2	1	1.1	0.3	0.5	26%
V	11	<1	1	1.0	0.0	0.0	0%
Si	11	5-59	17	21.9	17.9	4.2	82%
Na	11	3-55	10	16.0	15.2	3.9	95%
K	11	<1-9	2	3.3	2.8	1.7	86%
Mg	11	6-756	384	336.6	264.5	16.3	79%
Ca	11	89-6467	1782	1996.2	1543.4	39.3	77%
Ba	11	<1-5	1	1.6	1.4	1.2	84%
P	11	231-2237	890	989.7	474.8	21.8	48%
Zn	11	15-2532	1169	1144.1	581.0	24.1	51%
Mo	11	<1-142	42	57.0	42.1	6.5	74%
B	11	<5-196	0.05	119.9	146.7	12.1	122%
Viscosity (40C)	0	--	--	--	--	--	--
Viscosity (100C)	9	7.7**-18.3	13.6	13.1	3.3	1.8	25%
Soot (%)	6	<0.1-0.8	0.3	0.5	0.2	0.5	51%
Water (%)	11	<0.05-0.52	0.05	0.1	0.2	0.4	127%
	*Includes ATF and barrel of mixed oils						
	**Lowest viscosity due to ATF, Lowest WMO is 9.6						

Parameter	*Filtered Oils*						
	N	min-max	median	mean	±St Dev	variance	CV%
Fe (ppm)	8	28-192	70.5	83.1	53.0	7.3	64%
Cr	8	1-4	3.5	2.9	1.3	1.1	44%
Pb	8	<1-59	16	21.6	20.1	4.5	93%
Cu	8	7-255	27.5	53.0	77.4	8.8	146%
Sn	8	<1-4	2	2.3	1.0	1.0	43%
Al	8	3-13	8	7.8	3.7	1.9	48%
Ni	8	<1-5	1	2.1	1.7	1.3	80%
Ag	8	<1-1	1	1.0	0.0	0.0	0%
Ti	8	<1	1	1.0	0.0	0.0	0%
V	8	<1	1	1.0	0.0	0.0	0%
Si	8	4-49	30	26.1	14.4	3.8	55%
Na	8	5-66	11.5	23.5	22.5	4.7	96%
K	8	<1-10	2.5	4.5	3.8	2.0	85%
Mg	8	30-741	418	400.0	246.8	15.7	62%
Ca	8	977-2256	1572	1579.9	380.6	19.5	24%
Ba	8	<1-5	1	2.0	1.7	1.3	87%
P	8	696-982	844.5	852.5	94.4	9.7	11%
Zn	8	771-1248	1002	1027.9	150.9	12.3	15%
Mo	8	34-103	42	53.3	23.2	4.8	44%
B	8	<5-60	32	30.3	22.1	4.7	73%
Viscosity (40C)	0	--	--	--	--	--	--
Viscosity (100C)	5	9.9-16.9	13.3	12.8	2.6	1.6	20%
Soot (%)	3	<0.1-0.3	0.1	0.2	0.1	0.3	57%
Water (%)	8	--	0.05	0.2	0.2	0.4	93%

Parameter	*Virgin Oils**						
	N	min-max	median	mean	±St Dev	variance	CV%
Fe (ppm)	2	<1	1	1	0	0.0	0%
Cr	2	<1	1	1	0	0.0	0%
Pb	2	<1	1	1	0	0.0	0%
Cu	2	<1	1	1	0	0.0	0%
Sn	2	<1	1	1	0	0.0	0%
Al	2	<1	1	1	0	0.0	0%
Ni	2	<1	1	1	0	0.0	0%
Ag	2	<1	1	1	0	0.0	0%
Ti	2	<1	1	1	0	0.0	0%
V	2	<1	1	1	0	0.0	0%
Si	2	3-4	3.5	3.5	0.5	0.7	14%
Na	2	3-8	5.5	5.5	2.5	1.6	45%
K	2	<1	1	1	0	0.0	0%
Mg	2	10-921	465.5	465.5	455.5	21.3	98%
Ca	2	1078-2276	1677	1677	599	24.5	36%
Ba	2	<1	1	1	0	0.0	0%
P	2	803-1057	930	930	127	11.3	14%
Zn	2	1004-1296	1150	1150	146	12.1	13%
Mo	2	63-82	72.5	72.5	9.5	3.1	13%
B	2	<5-252	128.5	128.5	123.5	11.1	96%
Viscosity (40C)	2	63.1-110.4	86.75	86.75	23.65	4.9	27%
Viscosity (100C)	2	10.4-15.1	12.75	12.75	2.35	1.5	18%
Soot (%)	2	<0.01	0.01	0.01	0	0.0	0%
Water (%)	2	<0.05	0.05	0.05	0	0.0	0%

*SAE 15W40 and 5W30

Parameter	*Virgin Fuels**						
	N	min-max	median	mean	±St Dev	variance	CV%
Fe (ppm)	2	<1	1	1	0	0	0
Cr	2	<1	1	1	0	0	0
Pb	2	<1	1	1	0	0	0
Cu	2	<1	1	1	0	0	0
Sn	2	<1	1	1	0	0	0
Al	2	<1	1	1	0	0	0
Ni	2	<1	1	1	0	0	0
Ag	2	<1	1	1	0	0	0
Ti	2	<1	1	1	0	0	0
V	2	<1	1	1	0	0	0
Si	2	<1	1	1	0	0	0
Na	2	<1	1	1	0	0	0
K	2	<1	1	1	0	0	0
Mg	2	<1	1	1	0	0	0
Ca	2	<1	1	1	0	0	0
Ba	2	<1	1	1	0	0	0
P	2	<1	1	1	0	0	0
Zn	2	<1	1	1	0	0	0
Mo	2	<1	1	1	0	0	0
B	2	<5	5	5	0	0	0
Viscosity (40C)	0	--	--	--	--	--	--
Viscosity (100C)	2	1-1.7	1.35	1.35	0.35	0.59	26%
Soot (%)	2	<0.1	0.1	0.1	0	0	0
Water (%)	2	<0.05	0.05	0.1	0	0	0

*D2 diesel and B20 biodiesel

Appendix C: Gaussian Dispersion Model

Figure 20.4, Tables 20.1, and 20.2 are copied from *Air Pollution Control* (Cooper & Alley, 2011).

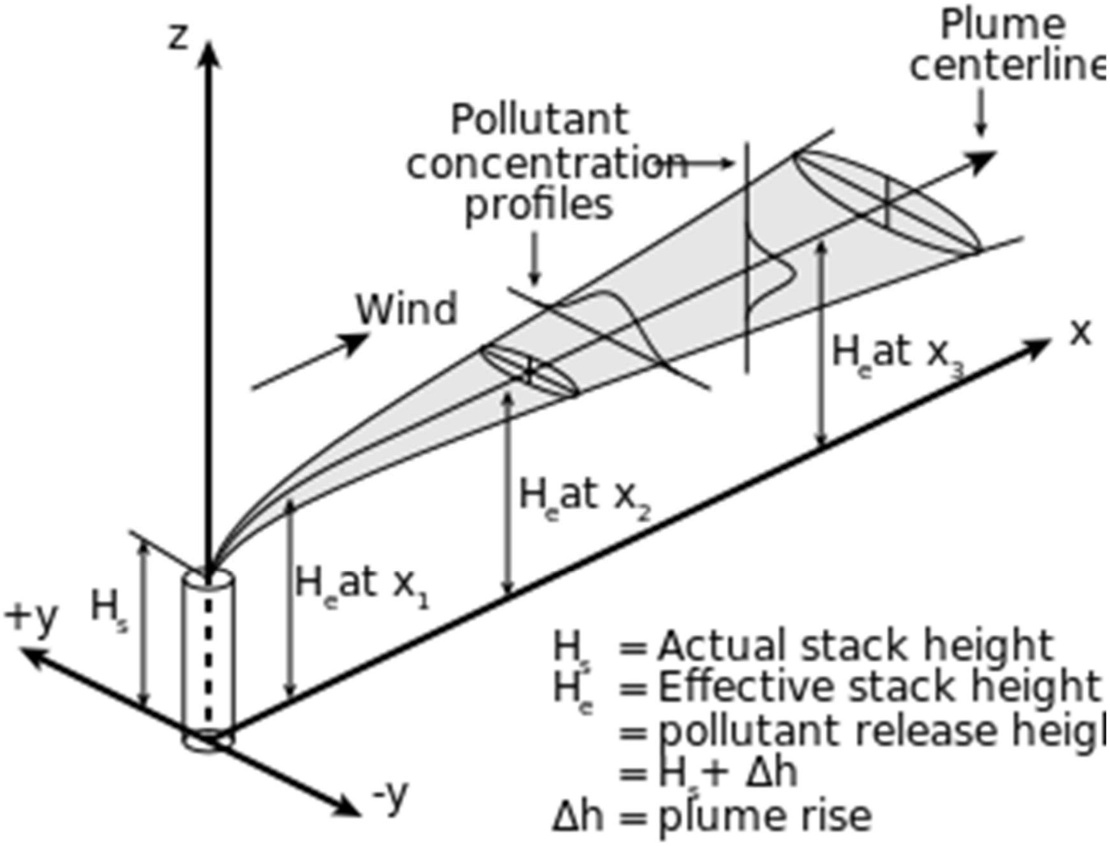

Figure 20.4 Coordinate system showing Gaussian distribution in the horizontal and vertical.

Table 20.1 Stability Classifications

	Day Incoming Solar Radiation			Night Cloudiness[e]	
Surface Wind Speed[a] [m/s]	Strong[b]	Moderate[c]	Slight[d]	Cloudy (≥4/8)	Clear (≤3/8)
<2	A	A-B[f]	B	E	F
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

[a] Surface wind speed is measured at 10m above the ground.

[b] Corresponds to clear summer day with sun higher than 60° above the horizon.

[c] Corresponds to a summer day with a few broken clouds, or a clear day with sun 35-60° above the horizon.

[d] Corresponds to a fall afternoon, or a cloudy summer day, or a clear summer day with the sun 15-35°.

[e] Cloudiness is defined as the fraction of sky covered by clouds.

[f] For A-B, B-C, or C-D conditions, average the values obtained for each.

*A=Very unstable
B=Moderately unstable
C=Slightly unstable
D=Neutral
E=Slightly stable
F=Stable

Regardless of wind speed, Class D should be assumed for overcast conditions, day or night.

Adapted from Turner, 1970.

Table 20.2 Values of Curve-Fit Constants for Calculating Dispersion Coefficients as a Function of Downwind Distance and Atmospheric Stability

			x < 1 km			**x > 1 km**		
Stability	**a**	**b**	**c**	**d**	**f**	**c**	**d**	**f**
A	213	0.894	440.8	1.941	9.27	459.7	2.094	-9.6
B	156	0.894	106.6	1.149	3.3	108.2	1.098	2.0
C	104	0.894	61.0	0.911	0	61.0	0.911	0
D	68	0.894	33.2	0.725	-1.7	44.5	0.516	-13.0
E	50.5	0.894	22.8	0.678	-1.3	55.4	0.305	-34.0
F	34	0.894	14.35	0.740	-0.35	62.6	0.180	-48.6

Adapted from Martin, 1970.

Acronyms

ACGIH	American Conference of Government Industrial Hygienists
AFIT	Air Force Institute of Technology
ASTM	American Society for Testing and Materials
ATF	Automatic Transmission Fluid
BEAR	Basic Expeditionary Airfield Resource
BPU	BEAR Power Unit
CEMIRT	Civil Engineer Maintenance Inspection and Repair Team
CFR	Code of Federal Regulations
CI	Compression Ignition
DEXMERC	ATF trade name meeting DEXRON and MERCON requirements
DoD	Department of Defense
EGR	Exhaust Gas Recirculation
EO	Executive Order
EPA	Environmental Protection Agency
GC	Gas Chromatography
GOV	Government Owned Vehicle
HDPE	High-Density Polyethylene
ICP-AES	Inductively Coupled Plasma - Atomic Emission Spectrometry
JSPPOH	Joint Service Pollution Prevention Opportunity Handbook
KTA	Manufacturer identifier: not an acronym
LDS	Manufacturer identifier: Inline, Diesel, Supercharged
LRS	Logistics Readiness Squadron
MCRS	Modular Common Rail System
MS	Mass Spectrometry
NIST	National Institute of Standards and Technology
NSPS	New Source Performance Standards
OSHA	Occupational Safety and Health Administration
PEL	Permissible Exposure Levels
PQ	Particle Quantity
QSK	Manufacturer identifier: not an acronym
RCRA	Resource Conservation and Recovery Act
SCR	Selective Catalytic Reduction
SEM	Scanning Electron Microscope
USAF	United States Air Force
WMO	Waste Motor Oil
WRM	War Reserve Materiel
WVO	Waste Vegetable Oil

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Vita

Captain Zachary S. Bierhaus graduated from South Decatur High School in Westport, Indiana in May 2006. He entered undergraduate studies at Rose-Hulman Institute of Technology in Terre Haute, Indiana where he graduated in May 2010 earning his Bachelors of Science in Mechanical Engineering with a concentration in Aerospace Engineering and a minor in Geography. He was commissioned through Detachment 218 AFROTC through Indiana State University.

His first assignment was at Laughlin AFB as a student in Undergraduate Pilot Training in October 2010. He was reclassified as a Civil Engineer and received orders to Minot AFB in May 2012 where he served as a project programmer, stood up the Operations Engineering element after an enterprise-wide reorganization, then was the Readiness & Emergency Management Flight Officer. In September 2015, he entered the Graduate School of Engineering and Management, Air Force Institute of Technology. Upon graduation, he will be assigned to the 635th Materiel Maintenance Squadron at Holloman AFB, NM.

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14. ABSTRACT

In an era of strict hazardous material restrictions and intense energy savings projects, DoD has an opportunity for a waste-to-energy initiative by looking to vintage diesel engine technology for inspiration. The idea comes in the form of recycled Waste Motor Oil (WMO) which can be used as a fuel in compression-ignition engines. When mixed at a low blend ratio, WMO can supplement diesel fuels to extend the range of fuel stores for electrical power generating equipment at contingency military bases while simultaneously decreasing the burden on fuel supply chain management and the hazardous waste disposal stream. This research looked at the feasibility of filtering, and then burning WMO blends. It also explored potential drawbacks which can threaten the lifespan of modern diesel engine components. Analytical methods included spectrometry, chromatography, viscometry, electron microscopy, and Gaussian dispersion modeling to study filtering method effectiveness, engine component wear, and air pollution effects. The WMO was diluted with diesel fuel to a point where metal concentrations were reduced to trace amounts which allowed engine exhaust emission levels to remain below permissible exposure levels without the assistance of engine emissions mitigation hardware. DoD can use these results for decisions-making when balancing energy security and environmental implications.

15. SUBJECT TERMS
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