INVESTIGATION OF THE EFFECTS OF HIGH SULFUR CONTENT ON THE OPERATIONAL CHARACTERISTICS OF A TIER 4 INTERIM ULS DIESEL ENGINE

by

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ABSTRACT

KILE ROSS STINSON. Investigation of the effects of high sulfur content on the operational characteristics of a Tier 4 Interim ULS diesel engine.
(Under the direction of DR. MESBAH UDDIN)

This thesis focuses on how high sulfur content diesel fuel impacts the operation of a Tier 4 Interim diesel engine designed to run on Ultra Low Sulfur Diesel (ULSD). This was explored because U.S. nuclear power plants have these engines as their secondary backups and each of the 99 U.S. nuclear power plants has up to 50,000 gallons of high sulfur diesel in emergency tanks that these engines would be run on. The 4.5L 99 HP test engine was run at 30%, 90% and 60% load, with sulfur concentrations of ULSD, 50 PPM, and 100 PPM. The 30% load tests showed as sulfur content was increased, the exhaust system temperatures also increased, with a maximum difference of 50°C. The 90% load test showed the same but with only a maximum difference of 20°C. The 60% load tests showed the 100 PPM sulfur fuel with the lowest exhaust system temperatures, the ULSD with the median, and 50 PPM with the highest. The DPF differential pressure soot loading rate of 0.03 g/L-hr was lower than the time-based rate of 0.06 g/L-hr, meaning the time parameter would trigger a regeneration first. The engine’s power output was constant, except for the 100 PPM fuel at 60% load, where a few runs showed the power output 10 HP lower than normal. This research concludes that the impact of up to 100 PPM fuel sulfur concentration was minimal on the test engine’s operational characteristics. Specifically, the engine would be put into regeneration by the time based soot loading, before any parameter that was influenced by sulfur concentration triggered it.

DEDICATION

To the Lord Jesus Christ, my wife, and parents for their support of this project.

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Mesbah Uddin, for his support and direction given for this project. I also want to thank Dr. Peter Tkacik, Dr. Jerre Hill, and Luke Woroniecki for their help and encouragement through my time here. I want to thank Stuart Gambill, Adit Misar, Clay Robinson and Spencer Owens for their work and contributions to this project. I also want to say thank you to Danny Alleman, Marty Bridges, and EPRI for coming to UNC Charlotte with this project, funding it, and their assistance with it.

TABLE OF CONTENTS

LIST OF FIGURES viii

LIST OF TABLES x

CHAPTER 1: INTRODUCTION 1

1.1 Literature Review 3

CHAPTER 2: TEST SET-UP 6

2.1 Hardware Selection 6

2.2 Test Plan Layout 10

CHAPTER 3: RESULTS AND DISCUSSION 14

3.1 30% Load Results 14

3.2 90% Load Results 20

3.3 60% Load Results 27

3.4 Miscellaneous Results 34

CHAPTER 4: CONCLUSION 38

4.1 Future Research 40

BIBLIOGRAPHY 42

LIST OF FIGURES

Figure 2.1: Image of flywheel designed for John Deere 4.5L test engine 8

Figure 2.2: Image of test engine docked up to engine dynamometer 8

Figure 2.3: John Deere Service Advisor 5 software screen shot with engine parameters that were recorded 9

Figure 3.1: DOC Inlet Temperatures for each of the sulfur concentrations at 30% load 15

Figure 3.2: DOC Outlet Temperatures for each of the sulfur concentrations at 30% load 15

Figure 3.3: DPF Outlet Temperatures for each of the sulfur concentrations at 30% load 16

Figure 3.4: EGR Temperatures for each of the sulfur concentrations for 30% load 16

Figure 3.5: DPF Soot Load based on measured differential pressure, for each of the sulfur concentrations at 30% load 18

Figure 3.6: DPF Soot Load based on fuel used, for each of the sulfur concentrations at 30% load 19

Figure 3.7: DPF Soot Load based on engine run time, for each of the sulfur concentrations at 30% load 20

Figure 3.8: DOC Inlet Temperatures for each of the sulfur concentrations at 90% load 22

Figure 3.9: DOC Outlet Temperatures for each of the sulfur concentrations at 90% load 22

Figure 3.10: DPF Outlet Temperatures for each of the sulfur concentrations at 90% load 23

Figure 3.11: EGR Temperatures for each of the sulfur concentrations at 90% load 24

Figure 3.12: DPF Soot Load based on measured differential pressure, for each of the sulfur concentration at 90% load 26

Figure 3.13: Engine coolant temperature for each of the sulfur concentrations at 90% load 26

Figure 3.14: DPF Soot Load based on fuel used, for each of the sulfur Concentrations at 90% load 27

Figure 3.15: DOC Inlet Temperatures for each of the sulfur concentrations at 60% load 29

Figure 3.16: DOC Outlet Temperatures for each of the sulfur concentrations at 60% load 29

Figure 3.17: DPF Outlet Temperatures for each of the sulfur concentrations at 60% load 30

Figure 3.18: EGR Temperatures for each of the sulfur concentrations at 60% load 30

Figure 3.19: DPF Soot Load based on measured differential pressure, for each of the sulfur concentrations at 60% load 33

Figure 3.20: DPF Soot Load based on fuel used, for each of the sulfur concentrations at 60% load 33

Figure 3.21: Power output of test engine for each of the sulfur concentrations, at 60% load 35

LIST OF TABLES

Table 2.1: Average and standard deviation of sulfur content of doped fuels, and sulfur content of ULSD 13

Table 3.1: Oil analysis results after each fuel concentration run 36

CHAPTER 1: INTRODUCTION

Nuclear power plants are a major source of electricity for the United States of America. While in a normal state of operation, nuclear power plants produce little environmental pollutants. However, with the process and materials required for nuclear power plants to generate electricity, if something goes wrong it can pose a major threat to the environment and surrounding population. This is why the plants have many fail safes and backups to try and reduce the risk of an incident happening. The Nuclear Regulatory Commission (NRC) is an agency of the United States government that oversees the nuclear power plants in the United States and regulates them to try and ensure safe operation.

In 2011, a power plant in Fukushima, Japan experienced an earthquake, followed by a tsunami. These events caused loss of power to the plant, and flooding of its back-up generators. With no power available to the plant, they were unable to pump cooling water to the nuclear fuel rods. This caused the fuel rod assemblies to melt down, and hydrogen gas explosions that released radioactive material into the atmosphere. In response to this accident, the NRC charged the nuclear plants located in the United States with developing a way to produce power and pump cooling water to the fuel rods in the event they lose power, and their back-up generators become not available.

The solution was to buy diesel engine powered generators and cooling pumps to store onsite, but away from the nuclear reactors. These engines would operate on an on-site, pre-existing, protected underground diesel fuel supply. The diesel engines that most nuclear power plants selected and bought were Interim Tier 4 engines.

The “Interim Tier 4” is a classification set by the Environmental Protection Agency (EPA) that is intended to reduce the emissions output by non-road diesel engines. This reduction in emissions is mainly achieved through the use of aftertreatment control technologies of the exhaust system, such as the use of exhaust gas recirculation (EGR), the use of a diesel oxidation catalyst (DOC), and a diesel particulate filter (DPF) [1]. These components of the exhaust system help the diesel engines meet the EPA standards, with the use of ultra-low sulfur diesel (ULSD), which contains 15 parts-per-million (PPM) of sulfur or less. However, the existing fuel supply at the nuclear power plant stations was purchased for equipment the plant had onsite long before the EPA Tier system was put in place. Each of the 99 U.S nuclear power plants have up to 50,000 gallons of diesel fuel in emergency storage tanks that contain up to 300 PPM sulfur content.

With the Interim Tier 4 engines, the engine control unit (ECU) monitors all the parameters of the engine. Once certain engine parameters meet a specific value, the ECU puts the engine into regeneration. In regeneration, the ECU increases the exhaust gas temperatures by different methods, to try and clean the DOC and DPF. The intervals between an engine needing regeneration vary depending on engine operating parameters, and it has been suspected that the sulfur content of the diesel fuel these engines would run on would negatively impact how these engines run and the time between service intervals. With the Interim Tier 4 engines being fairly new to the nuclear power plants, the process of regeneration is understood in theory, but not in practice, especially with the higher sulfur diesel fuel being used. The concern is that with the higher sulfur diesel that the nuclear plants have and would run these Interim Tier 4 engines on, the engine would go into regeneration at a time when the nuclear plant does not want/need them to. During certain regenerations, the engines have limited or no capability to carry load (which translates into not being able to generate electricity or pumping cooling water for the power plants).

This thesis investigates the effects of sulfur content on the operational characteristic of an Interim Tier 4 Ultra-low-sulfur diesel engine.

1.1 Literature Review

In 2006, the EPA ruled that the maximum allowable sulfur in diesel fuel could be 15 PPM (ULSD). Subsequent rulings on nitrogen oxide (NOx) levels, particulate matter (PM), and other emissions for diesel engines exhaust spawned a large amount of research into the effects of using ULSD in diesel engines. This included the performance of diesel engines on ULSD, and what kind of exhaust treatment was needed to deal with the ULSD and still meet the EPA regulations. The testing for this thesis was unique because the goal was to see how using high sulfur fuel would impact the performance of an engine designed to operate on ULSD, and how the exhaust aftertreatment would perform. Knowing that, there is not much research that investigates things from this perspective. However, there are a few reports that have useful information that can be referenced.

The first report that was studied was the “Diesel Emissions Control – Sulfur Effects Project (DECSE)” that was done by the U.S Department of Energy (DOE) in 2000 [3]. In this report, the DOE added sulfur to ULSD to raise the sulfur concentration of the fuel, or doped up the fuel. They doped the fuel up to 350 PPM for its test. The doping procedure used by the DOE was the foundation of the doping procedure developed for this project. Their testing included four common diesel engines that were readily commercially available. They tested each engine with; four different sulfur contents, each with four different test methods, and at 250 hours each. This shows the depth of the project, and the need for a government agency like the DOE to use their resources to conduct such test. Their endurance testing of up to 250 hours also partially shaped the test plan of this project. Results from their testing discovered that increasing sulfur content did increase the output PM. This is concerning for this current project because producing more PM will cause the DPF to clog faster. It also found that the regeneration temperature had to increase with higher sulfur fuel. This also could be a point of concern because the engine's ECU tries to keep a balance of the exhaust temperatures. The DOE tests also showed that increased sulfur content caused more sulfur ash to collect on the DOC, which reduces the NOx produced, but also can create an unwanted pressure or temperature difference across the DOC. This could cause the engine's ECU to shut the engine down.

Another study that gave some insight to this project was the "Analysis of the Influence of Fuel Sulfur Content on Diesel Engine Particulate Emissions," conducted at Pozan University of Technology in Poland [21]. In this test, they were interested in seeing how sulfur contents of 50 PPM to 2000 PPM impacted the PM output of the engines. They doped up their fuel as well, but used thiophene as the doping agent. Their engine test were only done in six minute intervals. Although this varies greatly from the test conducted in this thesis, if the engine was up to temperature and ran at a steady state, the results should still be useful for trends. Like the DOE test, their test results showed that as sulfur content increased, the amount of PM increased. This again brings up the point that increased PM could cause the exhaust system to prematurely clog and cause premature regeneration or not be able to clean itself with a regeneration.

One other study to note is the “Influence of fuel sulfur on the characterization of PM_{10} from a diesel engine,” from Beijing [22]. In this test, they studied how sulfur content impacted the PM and other emissions when sulfur content, and engine load were varied. They used 30 PPM and 500 PPM fuels that were delivered from the fuel manufacture with those sulfur contents. This was possible because those different grades of diesel were still available at that time. This was discussed for the project of this thesis, however after the EPA regulated almost all nonroad diesel engines run ULSD after 2014 this was not feasible because the lack of availability [23]. For their test, they used three load conditions, 30%, 60% and 80%, but ran the engine at two different RPM, 1400 RPM and 2300 RPM. This was because they were interested in trying to get results that might mimic that of an engine that would be run in the real world. Their results showed that PM increased with the 500 PPM fuel compared to the 30 PPM, which is consistent with other reports. It also shows that the heaviest concentration of PM occurred with the 500 PPM and lowest engine load. One interesting correlation this research made was that high engine load produced the highest rate of PM mass emission rate but with the smallest PM size. This means the exhaust aftertreament system would have to deal with a high rate of soot at high RPM but the soot would be small in size.

CHAPTER 2: TEST SET-UP

2.1 Hardware Selection

When this project was in the beginning stages, there were multiple ideas brought to light on how to test an engine, how to monitor and record data, which engine to test and for how long. Testing an engine in its onsite, real operational environment was out of the question because they would only be used in a major emergency. Operating the engines in the same way they would be used (running a generator or water pump) offsite was not an option either because the engine would need to be run for multiple extended periods of time and this would require load banks that the generator could supply power to or a large water supply and drain for the water pump. With the desire to have the engine operate in a controlled environment, and be able to easily record data, it was decided to test an engine on the water brake dynamometer on the UNC Charlotte grounds. With the testing location selected, an engine would need to be designated. After discussion with personal in the nuclear industry that had experience on what equipment was in the inventory of the nuclear power plants, a list of diesel engines was gathered that showed what and how many of the different kinds of engines were out there in the field. This list was then comparted to the physical size of the dynamometer test cell and load capacity of the water brake to be used, to determine which engine could be adequately tested. This is how it was settled that a John Deere Power Tech PWX 4.5L engine (model: 4045HFC92) would be tested.

Once the engine was settled on, the next step was to design a way to dock it up to the engine dynamometer. The engine dynamometer has existing carts for smaller automotive engines that were used to vertically raise the engine up so the crankshaft centerline was level with the engine dynamometer crankshaft centerline. The next step was to design how the crankshaft would output its power to the engine dynamometer. For the automotive engines that are normally run on this kind of engine dynamometer, a flywheel for most standard automotive engines is available. These are used by bolting the flywheel to the engine's crankshaft. Formed into that flywheel, is a bolt pattern to receive a constant velocity (CV) bearing with female splines. These spines match the male splines that are attached to a driveshaft that runs into the water brake. With this application not being standard, Figure 2.1 shows the flywheel that was designed and machined to fit the diesel engine and the dynamometer CV bearing. With the flywheel on the engine, it could be mated up to the engine dynamometer and physically be able to run.

The engine dynamometer used for this testing was a DTS Powermark water brake dynamometer with a Superflow data acquisition upgrade. Data collected by the engine dynamometer included engine RPM, power and torque. Other dynamometer parameters that were recorded include water brake temperature, water supply inlet valve position, water supply inlet pressure and atmospheric conditions. Figure 2.2 shows the test engine mounted on the engine dynamometer docking cart, docked up to the dynamometer.

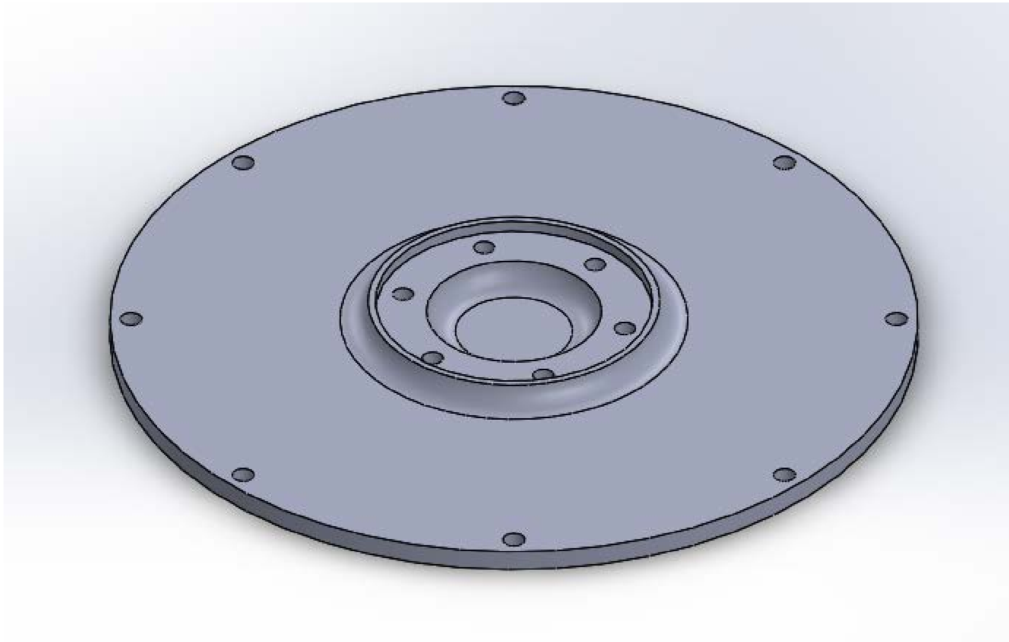

Figure 2.1: Image of flywheel designed for John Deere 4.5L test engine

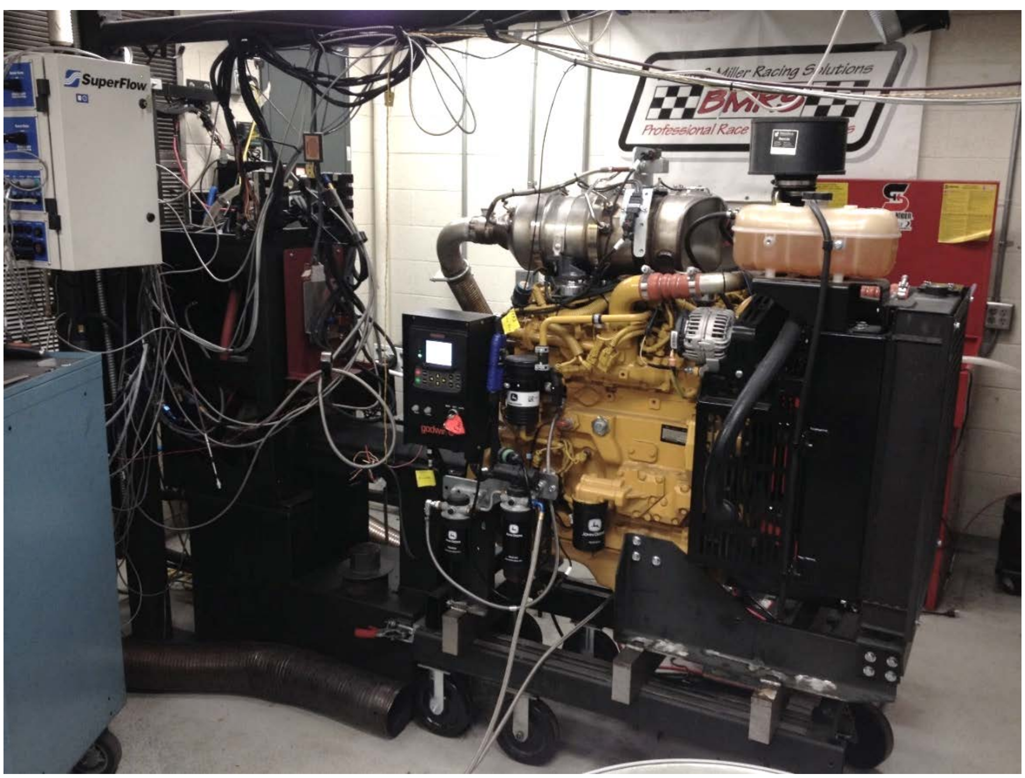

Figure 2.2: Image of test engine docked up to engine dynamometer

To record operating parameters from the engine, the John Deere Service Advisor 5 software was used. This software is designed by John Deere for their service technicians to use when they are servicing a John Deere engine or vehicle. The software connects to the ECU and can monitor and record any available channel that the ECU has. It does not have the ability to make operational changes, only view and record how the engine is running, diagnosis problems, and reset any alarms or service intervals. Many engine parameters were record, but the main data points that were of interest for this test were; DOC inlet temperature, DOC outlet temperature, EGR temperature, DPF differential pressure, DPF soot load – differential pressure based, DPF soot load – fuel based, DPF soot load – time based, and fuel rail pressure. Figure 2.3 is a screen shot from the Service Advisor software with all the parameters recorded being shown.

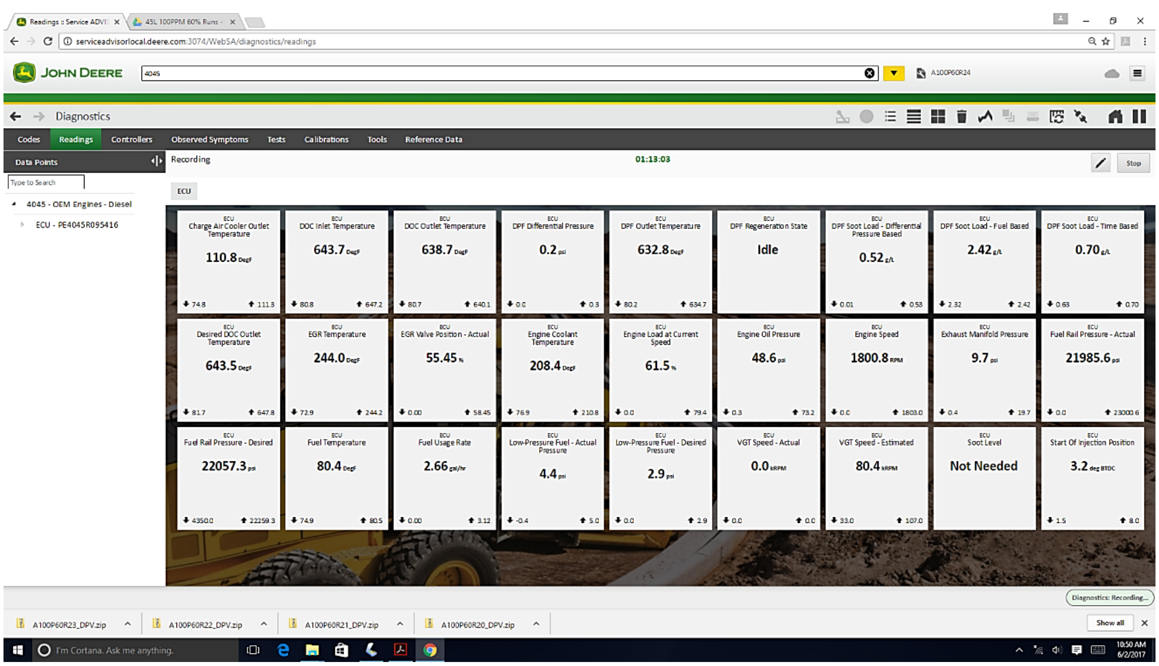

Figure 2.3: John Deere Service Advisor 5 software screen shot with engine parameters that were recorded

2.2 Test Plan Layout

The test plan was determined by speaking with personal in the nuclear industry that had experience with these engines, and how they would be operated in real life. It was determined that in the scenario these engines would be used, they would be ran at a constant load for about two hours, then shut down for a given period of time before being ran again for two hours. The design basis is that this would continue only up to 72 hours, in which time other pieces of equipment could be deployed in the field to take its place. When in use, these engines would see a constant load, however the power plants run these engines a couple times a year at different loads to make sure everything is working. How often, how long, and how loaded these engines are run in these checks varies between power plants, so a test plan was developed to take all this into account. The engine would be run at three different loads, 30%, 90% and 60%. At each of these loads the engine would be run for 12 hour, 12 hours, and 48 hours. The engine would be baselined with ULSD at these loads and run times, then the engine would be run on the same test plan with 50 PPM and 100 PPM fuel sulfur concentrations.

Estimates have been given that diesel fuel contains more than 10,000 isomers [2]. So to reduce the number of variables in this test, USLD was used for all testing. For the higher content sulfur runs, the USLD was doped with a sulfur containing compound, dibenzothiophene ($C_{12}H_8S$). This was chosen because it is considered one of the few most common sources of sulfur in diesel fuel [3]. It was also chosen because the singular molecule of sulfur requires more dopant to be added, which in turn allows for a greater resolution when weighing out the dopant to be added to the USLD. This reduces the margin of uncertainty, especially when small amounts of dopant are called for. To determine how much dibenzothiophene to add to the USLD, stoichiometrics was used. When a batch of fuel was received, a sample of it was sent off to a lab for a full spectrum analysis, which included sulfur content. With the sulfur content of the base fuel determined, it could then be properly doped with the correct amount of dibenzothiophene to reach the desired sulfur content. To determine the amount of sulfur needed to dope a barrel of fuel equation (2.2) was used, where the density of the diesel fuel (ρ_{diesel}) and base stock sulfur content ($S_{fuel\_as\_delivered}$) was given by the fuel analysis, and the desired sulfur content was given by ($S_{desired}$).

$$S_{add} = \left[\rho_{diesel} \left(S_{desired} - S_{fuel\_as\_delivered} \right) \right] \qquad 2.2$$

The amount of dibenzothiophene needed to reach the desired sulfur content was then found using equation (2.3). The molecular mass of dibenzothiophene ($\rho_{dibenzothiophene}$) and diesel fuel (ρ_{sulfur}) were taken from the periodic table, and the volume of diesel fuel (V_{fuel}) was measured as fuel was being dispensed into the fuel drum and checked with volume calculations of the fuel drum's physical dimensions.

$$D_{add} = S_{add} \left(\frac{\rho_{dibenzothiophene}}{\rho_{sulfur}} \right) V_{fuel} \qquad 2.3$$

Once a batch of fuel was doped, two samples were taken and sent out to two different labs to verify the new doped sulfur content. Each lab used a different test method (ASTM D3120 and ASTM D5453) as approved by the EPA to test sulfur in diesel fuels [3]. ASTM D3120 is a standardized test for determining the amount of sulfur in fuels. The sulfur content must be between 3 PPM and 1000 PPM for this test method to be valid. This test uses oxidative microcoulometry to determine the sulfur content. ASTM D3120 has a precision of 5 PPM for diesel [19]. The other test used was ASTM D5453, which is used to test fuels for sulfur using ultraviolet fluorescence. This test can detect sulfur content from 1 PPM up to 8000 PPM of sulfur, which is far beyond the upper limits of sulfur used in this test. The precision of this testing method at 100 PPM sulfur content would be 9 PPM [20]. At times, there were differences between the results of the two different test methods which were larger than the stated precision values. At least two instances occurred where there was more than a 20 PPM difference between them. Later investigation found that calibration on the ASTM D3120 test machine had fallen out of specification without the knowledge of the lab. This is why two different labs and two different test methods where done.

Table 2.1 shows the average and standard deviation of the sulfur content for all the doped fuel used during these tests. It also shows the average sulfur content result of the ULSD, to easily see the difference in sulfur contents of fuel being run between each sulfur concentration run. The standard deviation of the 50 PPM fuel was higher because this was the first sulfur concentration test done, and the doping procedure was still being refined at this early stage in the project. Care was taken to ensure homogeneity of the doped sulfur by frequent circulation of the fuel, and testing of the sulfur content at different depths of the fuel barrels.

Table 2.1: Average and standard deviation of sulfur content of doped fuels, and sulfur content of ULSD

	Average (PPM)	Standard Deviation (PPM)
50 PPM	51	7
100 PPM	99	5
ULSD	5	

CHAPTER 3: RESULTS AND DISCUSSION

The results of these test will be broken up into four different sections. The first, second and third sections will discuss the results of the 30%, 90% and 60% load test. Specifically, they will focus on the exhaust gas temperatures and accumulated mass concentrations on the exhaust aftertreatment system. The fourth section will discuss other results gathered over all the tests, including engine power production, fuel system performance, and lubricating oil characteristics.

3.1 30% Load Results

The first test that was run on each of the different fuel sulfur concentrations (ULSD, 50 PPM, 100 PPM) was the 30% load condition. The exhaust aftertreament system requires higher temperatures to active the catalyst [5]. So the 30% load condition test was done first because it was thought to be the worst operating condition for the aftertreament system. This round of testing included six runs of two hours each. The temperatures for the DOC inlet (Figure 3.1), DOC outlet (Figure 3.2), and DPF outlet (Figure 3.3) are shown below. Each graph shows six two hour runs at each of the sulfur concentrations, except for the ULSD run, which only shows four runs. Desired operating conditions require that each of these temperature be within 16°C of each other [6]. Each figure shows that is the case, however as sulfur content was increased, each respective temperature increased as well. This is desirable for the catalyst but poses other problems.

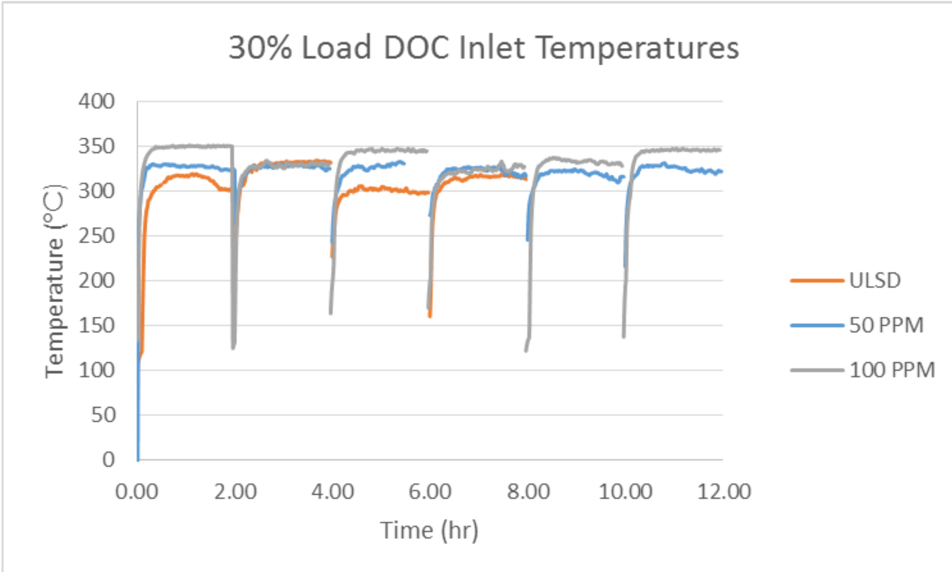

Figure 3.1: DOC Inlet Temperatures for each of the sulfur concentrations at 30% load

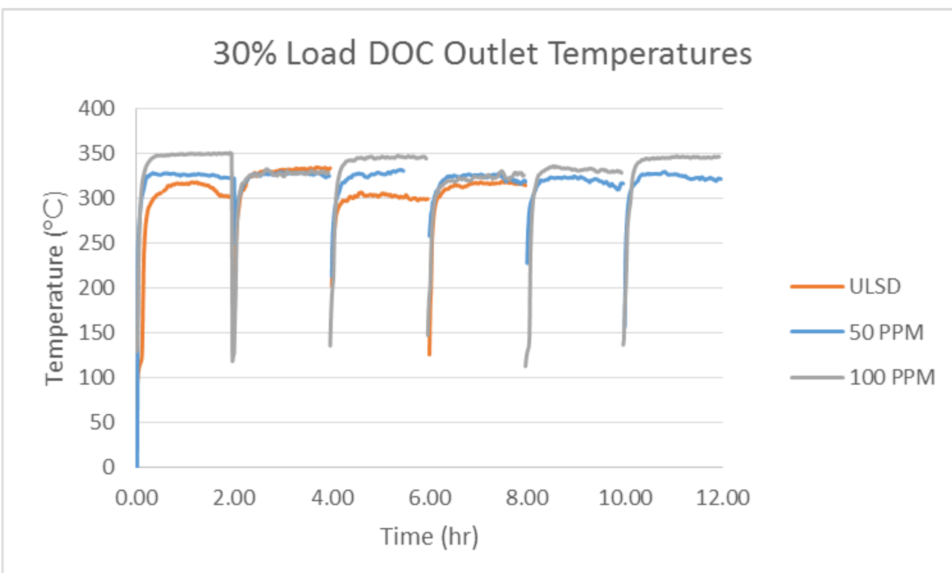

Figure 3.2: DOC Outlet Temperatures for each of the sulfur concentrations at 30% load

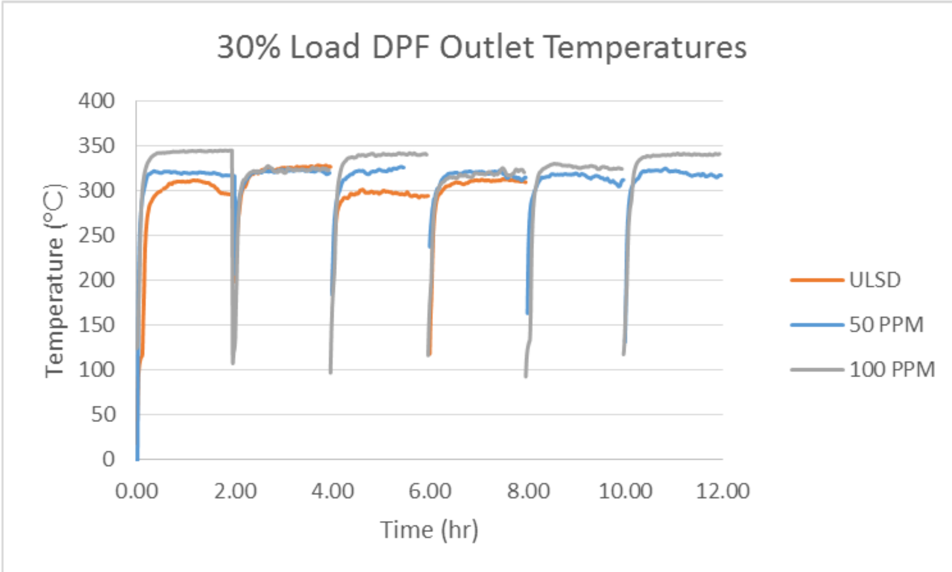

Figure 3.3: DPF Outlet Temperatures for each of the sulfur concentrations at 30% load

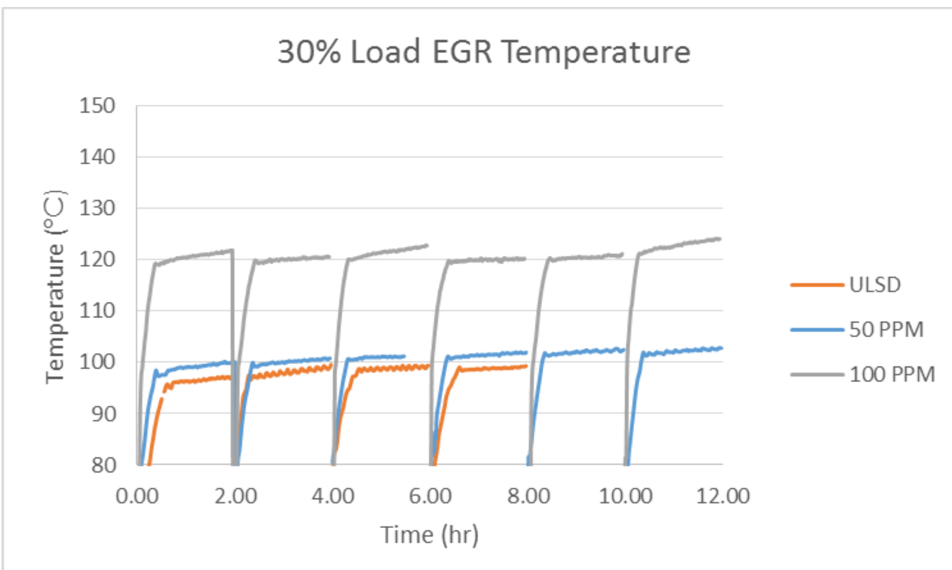

Figure 3.4: EGR Temperatures for each of the sulfur concentrations at 30% load

Figure 3.4 above, shows the EGR temperatures for each sulfur concentration. Like previous figures, this graph shows six two hour runs at each of the sulfur concentrations, with the ULSD run only showing four runs. After seeing a rise in DOC and DPF temperatures, a rise in EGR was expected but the 20°C higher EGR temperature difference in the 100 PPM runs versus the 50 PPM runs is interesting to note. EGR is used to decrease the nitrogen oxides (NOx) of an engine, at the cost of higher exhaust soot. A compromise is to cool the EGR charge, to reduce to the soot produced. With the rise of exhaust temperature, and the EGR not being able to be cooled as much, this would cause more soot to be produced [7]. This shows that the low load, lower sulfur concentration would produce less soot that the higher concentration. Although higher exhaust temperatures are desirable for increasing the catalyst efficiency [8], these temperatures are not high enough to offset the extra soot being produced.

The John Deere Service Advisor also recorded three different DPF soot loads; differential pressure based, fuel based, and time based. Figure 3.5 shows the differential pressure based soot load across the DPF for the three different sulfur concentrations at the 30% engine load. This value calculates a soot load, based on the pressure drop across the DPF as measured by the differential pressure sensor attached to the exhaust system [9]. Figure 3.5 shows what looks to be a large disparity between the different sulfur concentrations, however there are other factors that should be taken into account. The ULSD runs only have four runs shown (like previous figures) however the engine had been run for over 7 hours before data was taken. This also was part of the break in period of the engine, and could contribute to this. Another thing that needs to be considered is that a regeneration was done after the ULSD test. A regeneration was done after the 50 PPM test as well, however there were 30 hours of engine run time after the regeneration, but before the 100 PPM test was started. The test was conducted this way because this is how these engines would be ran in the field, and due to a change in the testing method by the project sponsor part way through the test. With this considered, Figure 3.5 still indicates a higher pressure drop over the DPF for the 100 PPM fuel, over the other sulfur concentrations, but it does not significantly increase, and is well below the threshold of the allowable limit of 3 g/L [10].

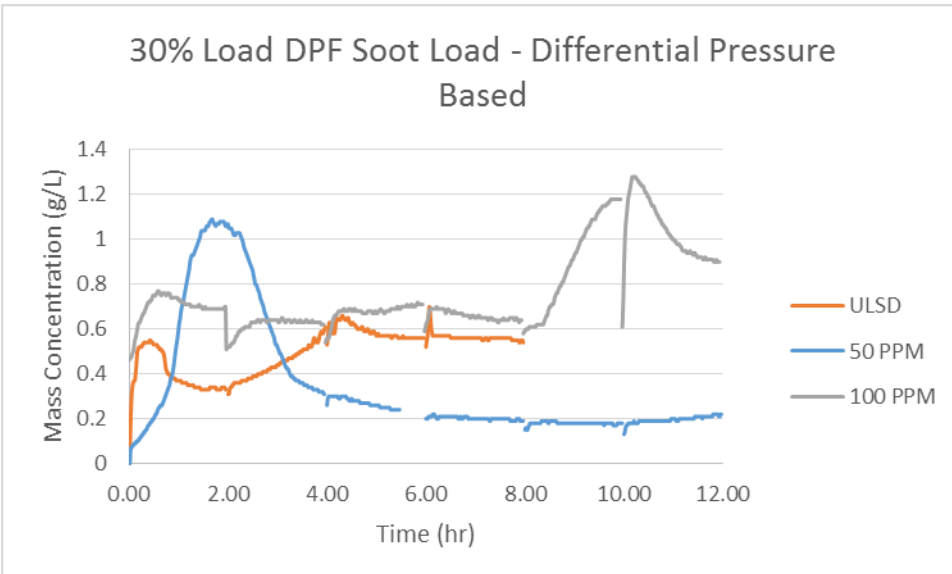

Figure 3.5: DPF Soot Load based on measured differential pressure, for each of the sulfur concentrations at 30% load

Figure 3.6 shows the DPF Soot Load based on fuel usage, for each sulfur concentration at 30% load. Although the values recorded are referred to as based on fuel usage, this is not the only thing that goes into these values. This is a calculated value that takes into account many unspecified factors and is more appropriately stated as a mass balance based model in the manual [10]. With that understanding, the figure makes more sense that they are not liner since the load was constant. The cause for the shift in start points for each sulfur content can again be attributed to the duration between regenerations, which reset these values after the regeneration had taken place. The trend for each sulfur content shows that the soot level based on fuel usage level off around 2.5 g/L, which like the soot load based on differential pressure, is under the threshold.

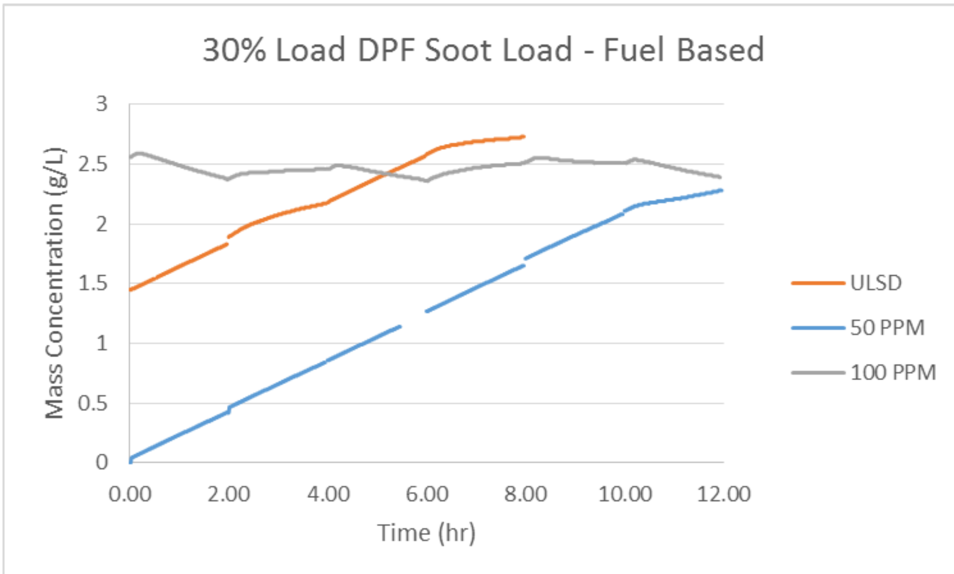

Figure 3.6: DPF Soot Load based on fuel used, for each of the sulfur concentrations at 30% load

Figure 3.7 shows the DPF soot load based on engine run time for each sulfur content at 30% load. This value is only based on how long the engine has run since the last regeneration cycle, and therefore the sulfur content of the fuel, or engine load have no bearing on these values. Like other figures, the disparity between the initial starting values is from the duration of time since the last regeneration took place. The other load tests showed similar results, and therefore will be omitted from further discussion.

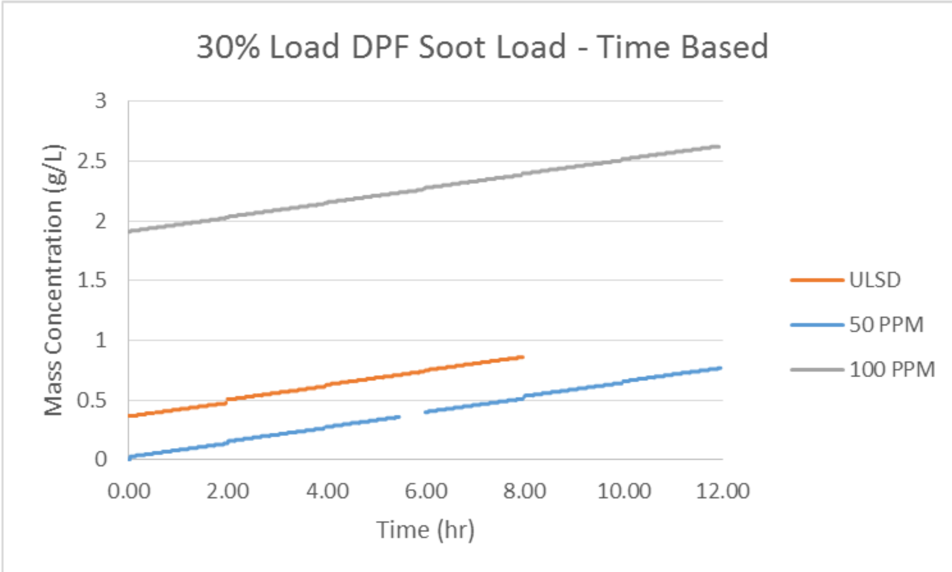

Figure 3.7: DPF Soot Load based on engine run time, for each of the sulfur concentrations at 30% load

These results show that at 30% load, there wasn't much of an operational difference between the ULSD and 50 PPM fuel. However, the 100 PPM fuel did show a faster rise in DPF pressure differential soot load and higher levels. Although the 100 PPM fuel did show a difference, it was below the allowable threshold. At the 30% load, all three different sulfur content fuels allowed the engine to passively clean the DPF and DOC. This means that if the engine was run at these conditions for an extended period of time, regeneration would occur on the DPF soot load timer before the other parameters got high enough to trigger a regeneration. This would be classified as normal operating condition, and therefore the sulfur content does not change how the engine would operate.

3.2 90% Load Results

The second test that was run on each of the different fuel sulfur concentrations was the 90% load condition. Like the 30% load, this round of testing included six runs of two hours each. This test was done next because very few power stations run their engines at very high loads. Therefore, it was decided to set this load condition at the same run time as the 30% load. The temperatures for the DOC inlet (Figure 3.8), DOC outlet (Figure 3.9), and DPF outlet (Figure 3.10) are shown below. As stated earlier, the desired operating conditions should be within 16°C of each other, and they were. As with the 30% load tests, the temperatures increased as the sulfur content was increased. The higher sulfur fuel can cause sulfur to be deposited on the surface of DOC and not be removed until a high load or high temperature condition exists, like a high load like this or regeneration. When the sulfur does get burned off of the DOC it is converted into sulfur dioxide (SO_2) [11]. This is not desirable for emissions, but does not cause the immediate operation of the engine to change. With the higher load though, the amount of fuel being used is increased, which deposits more sulfur on the catalysts. With that and the higher exhaust temperature that the higher sulfur causes, it could cause premature aging of the DOC [12]. This would not be ideal for an engine that is run constantly, but with the little time these engines are in service in the field, it should not change their operation or maintenance schedule. The overall temperatures of the DOC and DPF are increased because of the increased load.

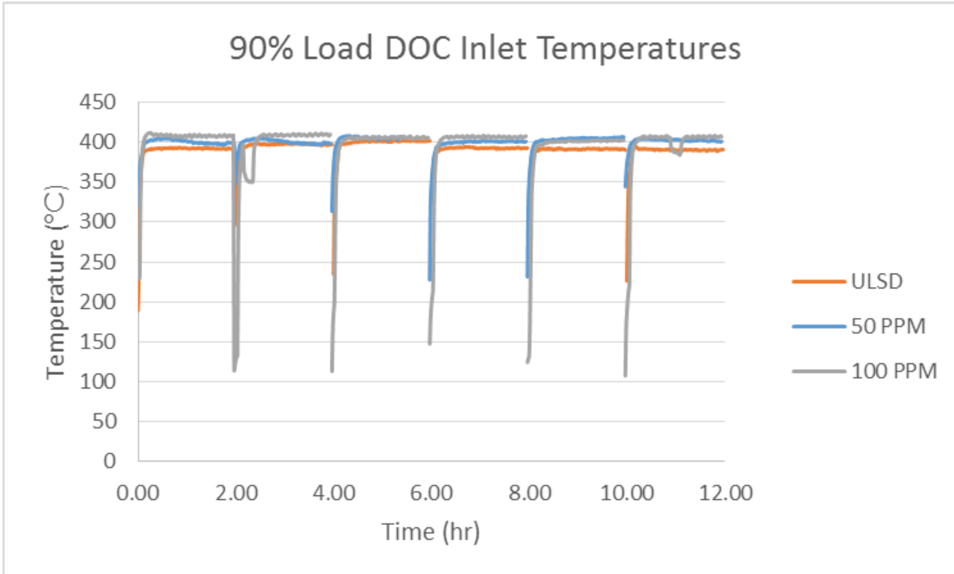

Figure 3.8: DOC Inlet Temperatures for each of the sulfur concentrations at 90% load

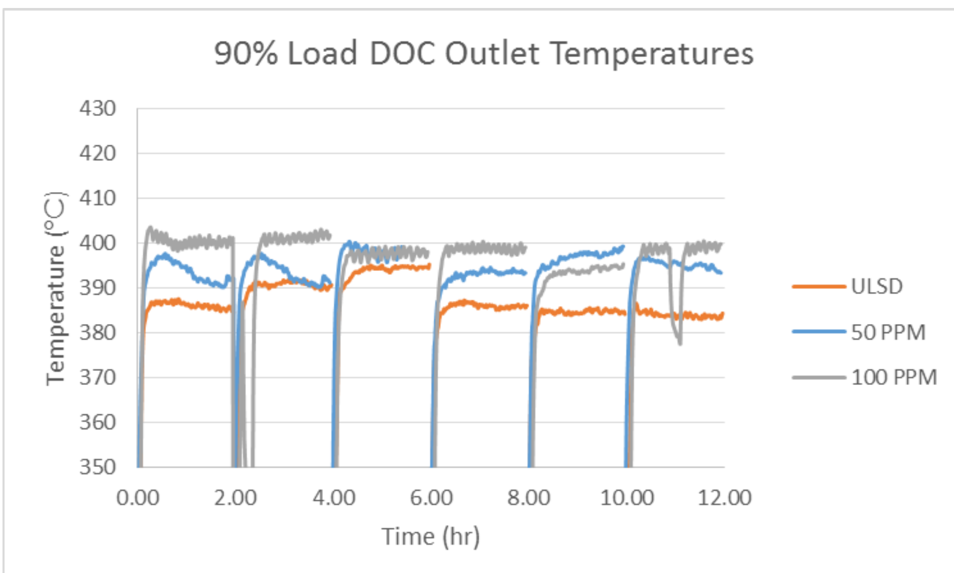

Figure 3.9: DOC Outlet Temperatures for each of the sulfur concentrations at 90% load

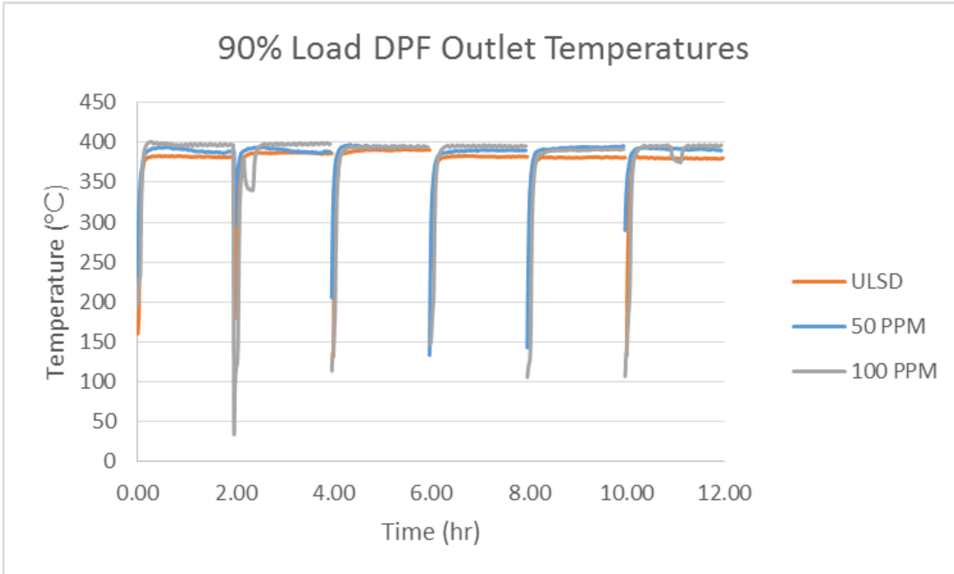

Figure 3.10: DPF Outlet Temperatures for each of the sulfur concentrations at 90% load

Figure 3.11 shows the EGR temperatures for each of the different sulfur concentrations for the 90% load tests. Like the 30% load tests, as the sulfur concentration was increased, the EGR temperature increased as well. This can be attributed to the increase exhaust gas temperatures, like the 30% load test showed as well. The average temperature difference between the ULSD and 100 PPM sulfur fuel was roughly the same between the 30% and 90% load. However, the 50 PPM fuel showed an increase in average temperature of a few degrees between the 30% and 90% load.

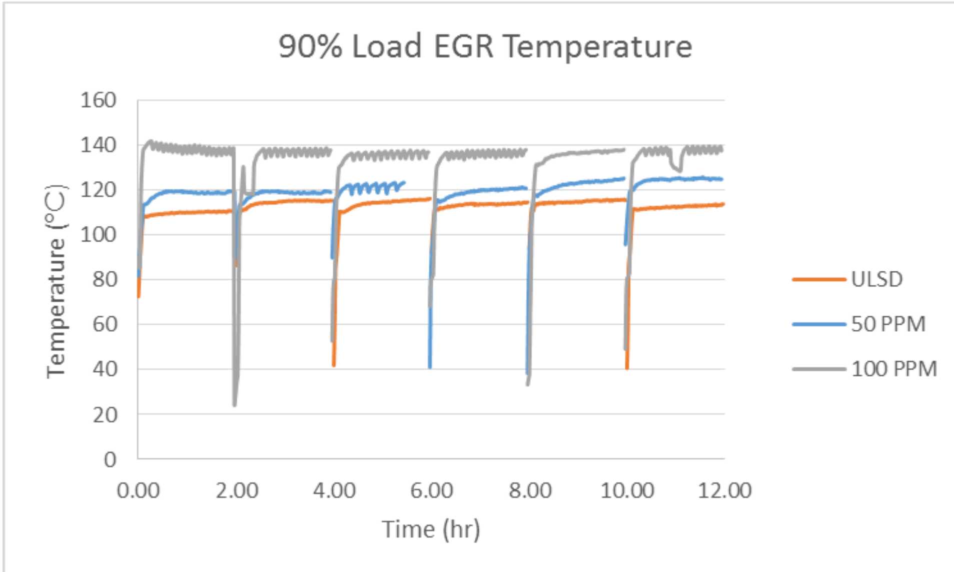

Figure 3.11: EGR Temperatures for each of the sulfur concentrations at 90% load

Figure 3.12 shows the DPF soot load based on measured differential pressure, for each sulfur concentration at 90% load. Like other figures, the disparity between the initial starting values is from the difference in times between regeneration. This figure shows the rate of the differential pressure based soot load increased about the same for each of the sulfur concentrations, which was 0.03 g/L-hr. This is important to know because the differential pressure based soot load rate of change is less than that of the time-based soot load parameter, which was 0.06 g/L-hr. This means that at 90% load, sulfur content does not seem to influence the operational parameters that force a regeneration, and the time-based soot loading parameter will be the factor that triggers that event. Although sulfur content in fuel does impact the operational performance of the DPF [13], it doesn't influence it enough to make a difference in the operating time and range of these test that mimic the field running conditions for these engines. Another point of interest in Figure 3.12 is the instability and fluctuations in the 100 PPM fuel run. The ULSD and 50 PPM runs do have a small amount of fluctuations in them, but their trend is mostly linear increasing. The 100 PPM fuel has a larger total difference between the beginning and end of the test, and some runs display data values that have a sinusoidal function. This could be related to the fluctuations seen in the temperature figures above for the 90% load conditions. It is believed that these temperature fluctuations are a result of the engine coolant fan tuning on and off throughout the test to regulate engine temperature, as observed. Figure 3.13 shows the engine coolant temperature for each of the different sulfur content fuels for the 90% load tests. This operation of the fan appears odd however because for the ULSD fuel there is only a 7°C engine coolant temperature difference between the 100 PPM fuel, and the 50 PPM fuel only had a 2°C difference. With this little temperature difference, it does not seem that would cause the coolant fan to constantly be turning on and off, but the temperature oscillations did occur only when the engine coolant temperature reached 105°C. As stated earlier, the emission controls of these engines reduce NOx through the use of EGR, but in doing so cause more soot and have higher in-cylinder temperatures, which causes the engine to operate at a higher temperature [14].

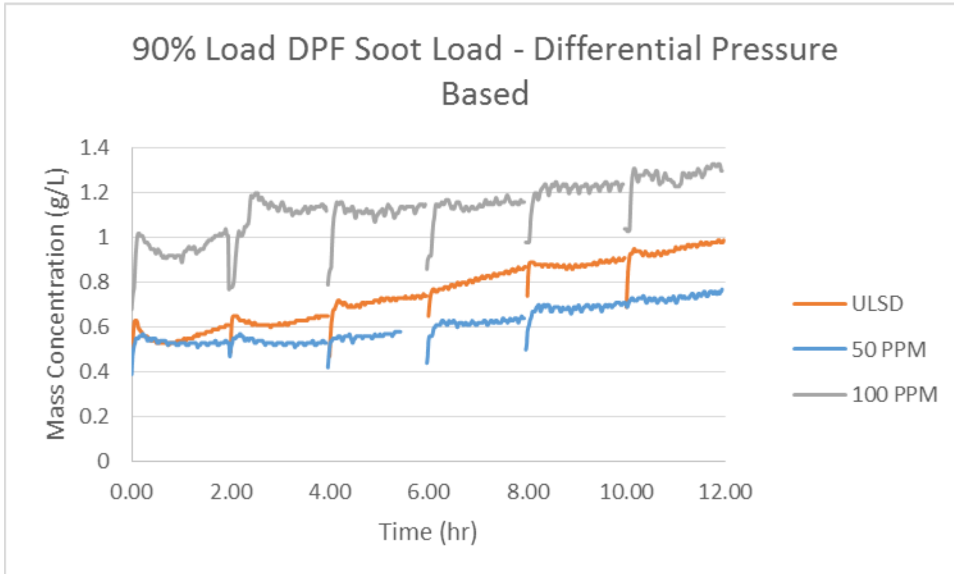

Figure 3.12: DPF Soot Load based on measured differential pressure, for each of the sulfur concentrations at 90% load

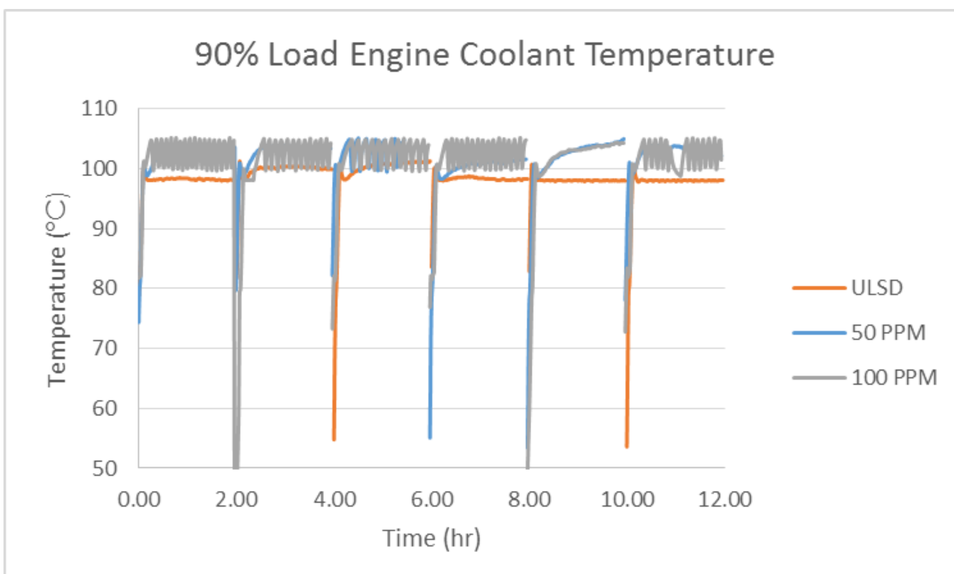

Figure 3.13: Engine coolant for each of the sulfur concentrations at 90% load

Figure 3.14 shows the DPF soot loading based on fuel used for each of the sulfur content fuels at 90% load. This varies greatly from the same figure for the 30% load tests

(Figure 3.6) because that figure shows an increase in soot loading until around 2.5 g/L, where all three sulfur concentrations look to level off. This figure for 90% load, decreases the soot loading down to 1.5 g/L, then seems to level off. As discussed earlier, this soot loading has many unknow factors that go into it, not just fuel used. This figure shows that engine load must factor into this parameter, as it was the only change between the two different load tests. This agrees with the general consensus that increased engine loading increases soot production, however the elevated temperatures and flow rates help reduce soot loading on the DPF [15].

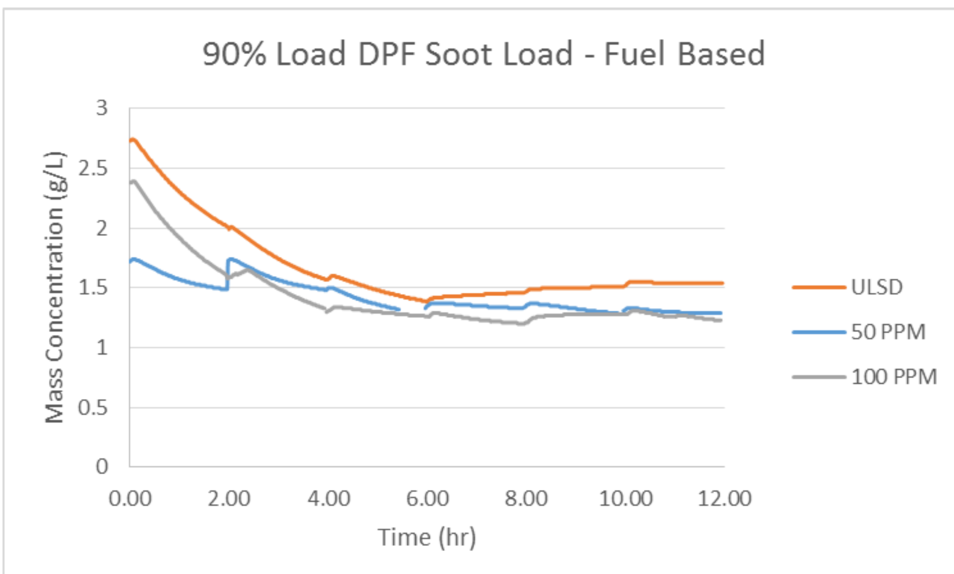

Figure 3.14: DPF Soot Load based on fuel used, for each of the sulfur concentrations at 90% load

3.3 60% Load Results

The third set of tests that were run on each of the different fuel sulfur concentrations was the 60% load condition. This round of testing included 24 runs of two hours each. This round of testing was lengthened because it was determined the 60% load is where most of the power stations operate their engines. The temperatures of the DOC inlet, DOC outlet and DPF outlet are shown in Figure 3.15, Figure 3.16 and Figure 3.17. Like the other load conditions, each of these temperatures were within the operating parameter of 16°C of each other, within each of the sulfur concentrations. Unlike the other load conditions where increasing sulfur content increased the temperatures, this 60% load condition showed that the 100 PPM fuel had the lowest temperatures, then the ULSD, and the 50 PPM had the highest exhaust temperatures. A point of interest is the spike in all the temperatures for the 100 PPM fuel test around the 36-hour mark. This is an indication of a regeneration. This regeneration was initiated by the time-based soot loading limit. When the engine put itself into regeneration, it maintained RPM (1800) and load (60%) initially. As load was increased up to 90%, the engine derated to 1200 RPM but held the desired load. This is of interest depending on what the engine would be driving in service in the field. If it were driving a generator this would be an issue because the engine RPM change would change the frequency of electricity being produced. For engines driving water pumps, this would change the flow rate of water being pumped. This was not believed to be dependent on sulfur content of fuel, but instead on the limitations of the engine and how the ECU controls the engine while in normal regeneration. The regeneration does show that that temperature of the DOC inlet is lower than that of the DOC outlet and DPF outlet. This is consistent with conventional regeneration behavior, as the particulate matter on the DPF inlet face combust with oxygen in the exhaust above 600°C [16]. With the combustion of the particulate matter going on between the DOC and DPF, this explains why the temperature is higher after the

DOC. After the regeneration was over, all temperatures returned to their normal operating levels.

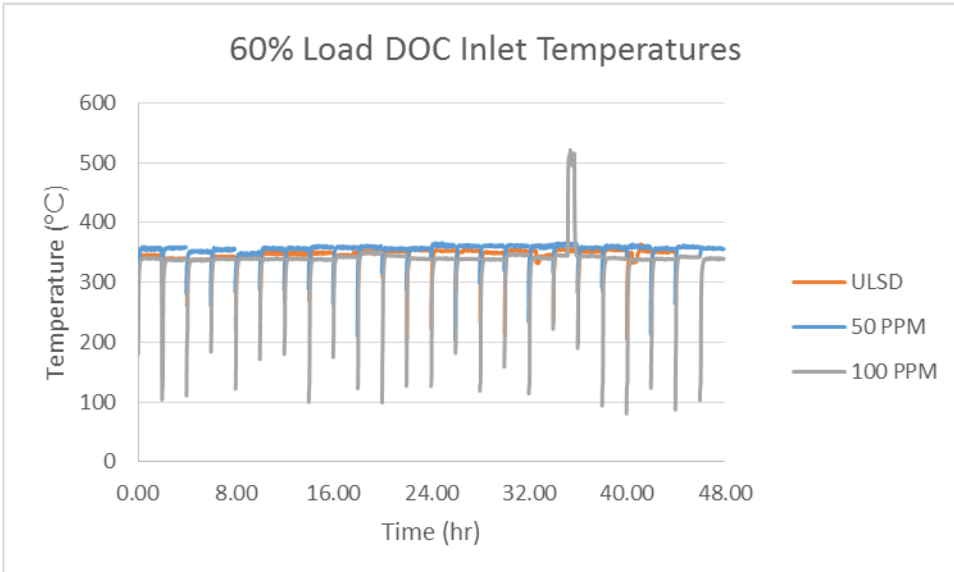

Figure 3.15: DOC Inlet Temperatures for each of the sulfur concentrations at 60% load

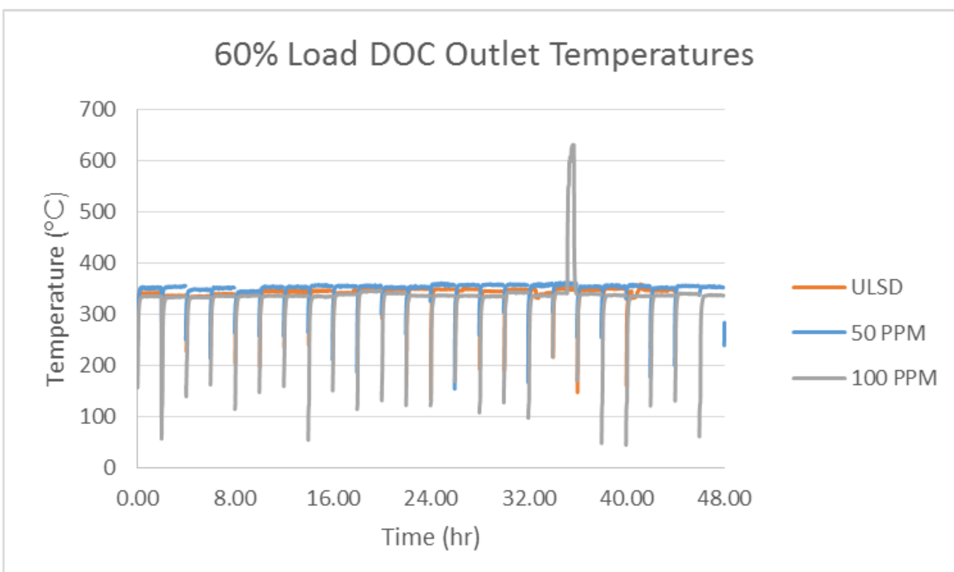

Figure 3.16: DOC Outlet Temperatures for each of the sulfur concentrations at 60% load

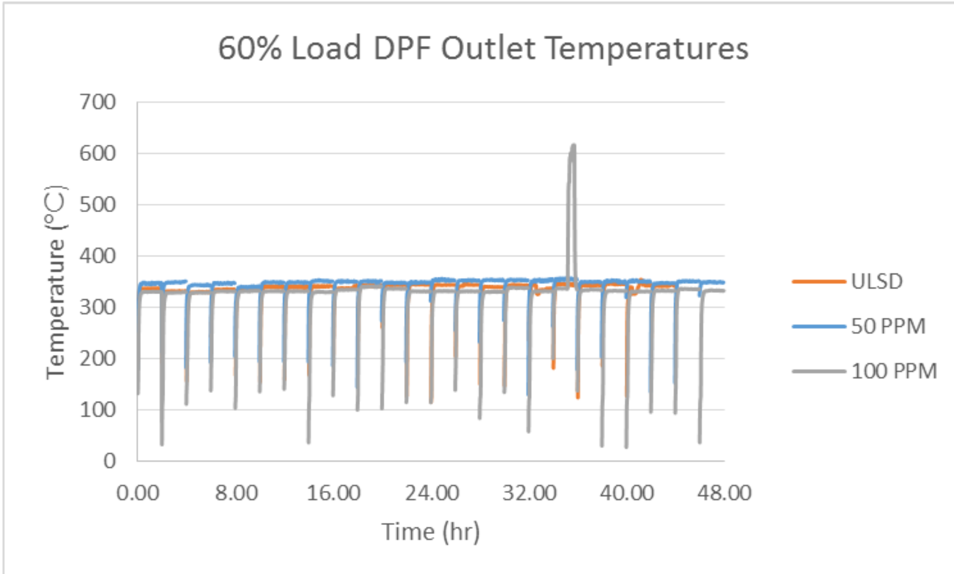

Figure 3.17: DPF Outlet Temperatures for each of the sulfur concentrations at 60% load

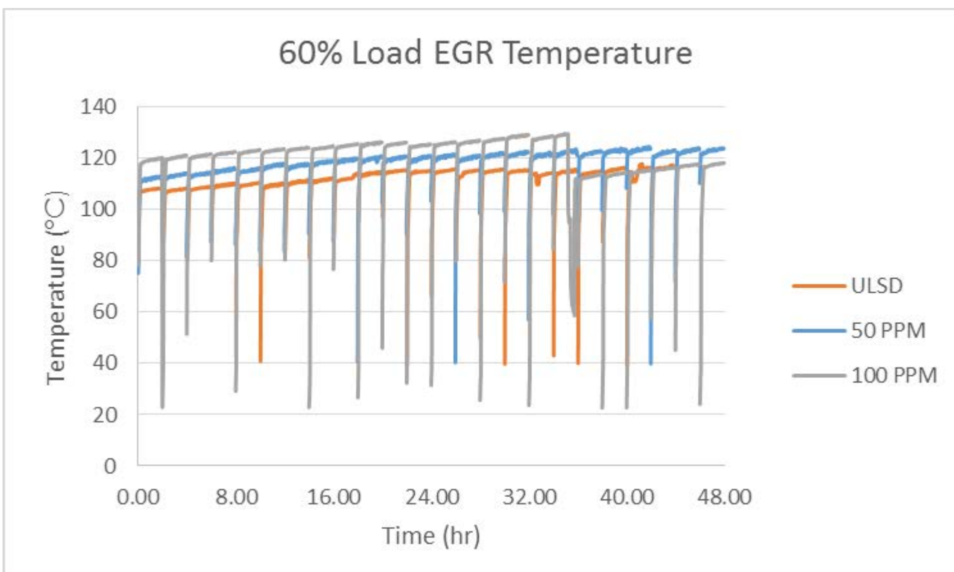

Figure 3.18: EGR Temperatures for each of the sulfur concentrations at 60% load

Figure 3.18, shows the EGR temperatures for each of the sulfur test at 60% load. Like the other load conditions, the higher sulfur content fuels had higher EGR temperatures, however the difference wasn’t as significant. For 30% and 90% loads, the temperature difference between the ULSD and 50 PPM runs were 5-10°C, and the difference between the ULSD and 100 PPM runs were 20-25°C. However, the 60% load showed a 10°C temperature difference between all three sulfur contents. One interesting observation is that for each sulfur fuel concentration, the EGR temperature gradually rises over the 35 hours of 60% load run time, before regeneration occurred. Then after regeneration, the EGR temperature of the 100 PPM runs, dropped to below that of the ULSD runs, at the same given time point, but started rising at the same rate as before regeneration. This could be attributed to a few different things. One theory from literature suggest that deposits of soot and hydrocarbons can build up in the EGR cooler, and cause a reduction in the heat transfer properties, as well as increase the pressure drop across the EGR cooler and reduce the engine efficiency [17]. Another theory could be that because of the increased sulfur content of the fuel, EGR cooler fouling and corrosion could occur from the sulfates that are a by-product of combustion with sulfur containing fuels [18]. These seem to be only partial answers, as the EGR temperature dropped significantly (20°C) after regeneration. Since the recorded EGR temperature did not increase enough to burn off deposits, more investigation and testing should be done to understand this phenomenon.

Figure 3.19 shows the DPF soot load based on differential pressure for all the sulfur concentrations at the 60% load condition. Like the previous DPF soot loading figures based on differential pressure, the 100 PPM fuel had the highest mass concentration, but this was due to the difference in time between regenerations. In general, all three sulfur concentration fuels showed the same rate of soot loading on the DPF. Figure 3.19 shows very similar characteristics to that of the same figure for 90%

load, Figure 3.12. This is, that there is a very steady and almost linear increase in the soot loading over the run time, except for that of the 100 PPM runs. The 100 PPM runs do increase; however, it is much more sporadic with spikes in the data up and down, much like the 30% load displayed. Figure 3.19 also shows the regeneration at the 35-hour mark, and the change in the differential pressure soot loading is very noticeable. After regeneration, the soot loading was shown to drop to normal post-regeneration levels, and start to increase at close to the same rate as the other fuel concentrations. The rate of differential pressure based soot load increased about the same for the ULSD and 50 PPM fuels at 0.02 g/L-hr, but the 100 PPM fuel had a slight increase of soot loading rate at 0.03 g/L-hr. This is important to know because the differential pressure based soot load rate of change of the ULSD, 50 PPM and 100 PPM fuels is less than that of the time-based soot load parameter, which was 0.06 g/L-hr. This means that at 60% load, the sulfur content does not seem to influence the operational parameters enough to force a regeneration, and the time-based soot loading parameter will be the factor that triggers that event.

Figure 3.20 shows the DPF soot loading for fuel used of each sulfur concentration at 60% load. This figure reaffirms the result of the same figure for the 90% load (Figure 3.12), that shows this soot loading value takes into account many factors. One can determine the regeneration point aligns with that of the other data. After the regeneration, the 100 PPM fuel comes back up to the pre-generation soot lever loads, meaning these values are probably more weighted on engine RPM and load.

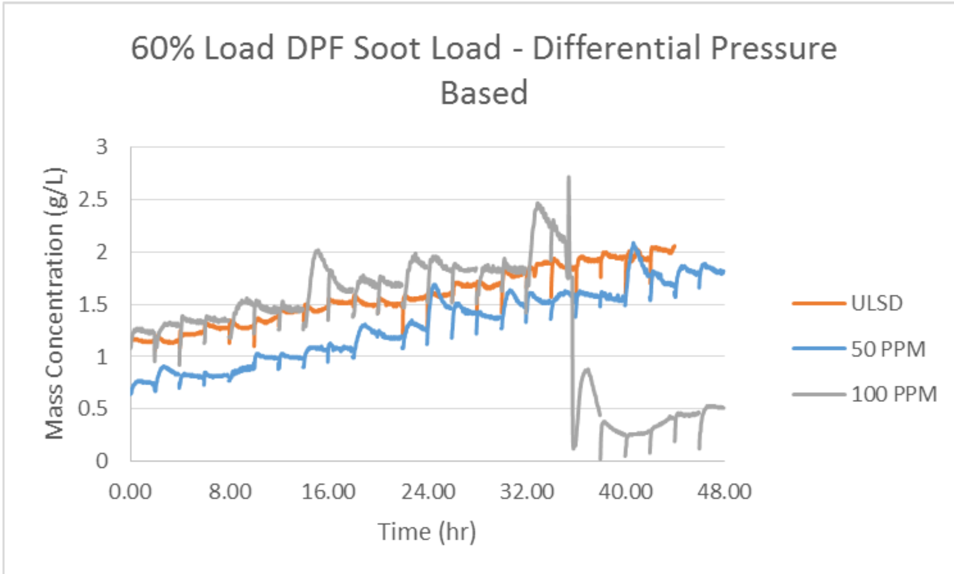

Figure 3.19: DPF Soot Load based on differential pressure, for each of the sulfur concentrations at 60% load

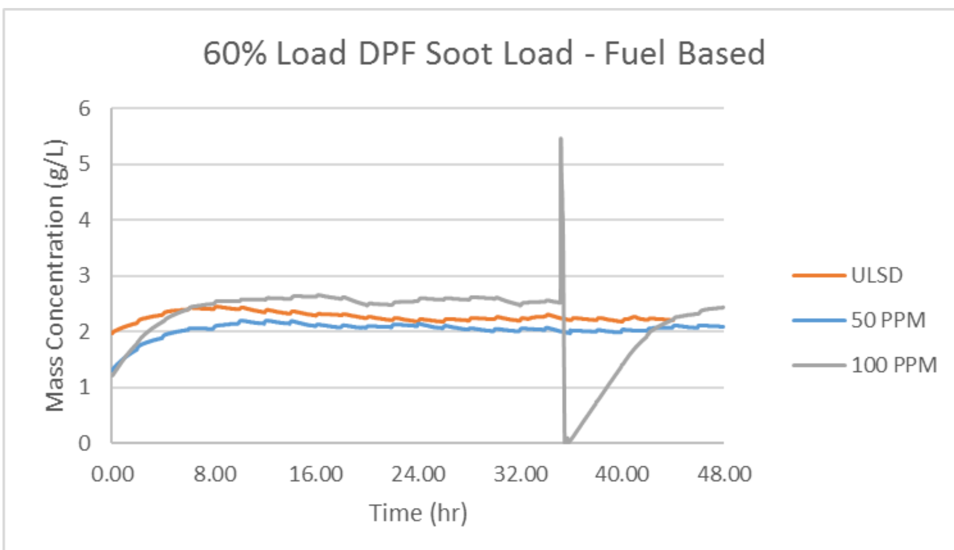

Figure 3.20: DPF Soot Load based on fuel used, for each of the sulfur concentrations at 60% load

3.4 Miscellaneous Results

One of the major measures of an engine's performance is the power and torque it outputs. For all of the testing on this engine, only the 100 PPM fuel at 60% showed a power difference. Figure 3.21 shows the power output of the test engine for each sulfur concentration at 60% load. In some places, a 10 HP difference can be observed. This does raise concern, and peaks interest in the results. One explanation could be that with the higher sulfur fuel, and increased amount of EGR, the engine makes less power because the EGR takes the place of some oxygen in the combustion chamber, which reduces the power output of the engine. If that was the case, one would expect to see the power output of the test engine to be constantly reduced, which it is not. Another explanation could be the slow creep of the engine dynamometer loading condition of the engine and/or the slight change in the engine's control unit and how it responds to the engine dynamometer load. More tests are needed to make sure this result is repeatable, and to give more data points to give insight into this.

Fuel pressure was also monitored as a concern was the higher sulfur content fuels would clog the fuel filter. Both the low pressure and high-pressure side of the fuel system was monitored but showed no change in fuel pressure for either. Therefore, for this amount of run time, sulfur concentrations, and engine loads, sulfur content did not change how the engine operated.

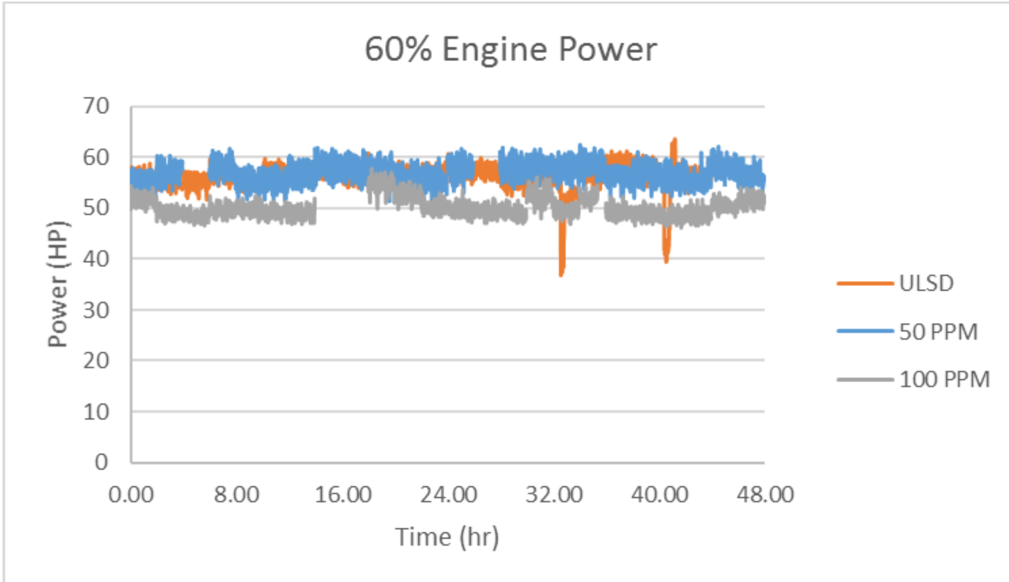

Figure 3.21: Power output of test engine for each of the sulfur concentrations, at 60% load

Properties of the engine lubrication oil were also investigated. The USLD runs were in the break-in period of the engine. After the ULSD runs were complete, the break-in period for the engine was complete. The oil was changed and an oil sample taken and sent off for analysis. The oil analysis after the ULSD runs showed trace amounts of wear metals in the oil, which were expected as this was considered the break-in period for the engine. Fuel contamination and soot levels in the oil showed less than the measurable value of the test. The viscosity is a measure of a fluid's ability to resist flow and shear and is considered the most important physical property of oil [26]. At 100°C, the first oil test showed that oil still was still within operating range for the 10W-30 oil that was recommended for the break-in period, and would be considered ok to keep using based on oil properties [25]. The total base number (TBN) is the value that shows the ability of the oil to neutralize the by-products of combustion and keep the oil from becoming too acidic, which could cause corrosion to the internal engine components [27]. The TBN of the oil after the break-in period was still within operating conditions as well [28] [29].

Table 3.1: Oil analysis results after each fuel concentration run

	Run Hours	Fuel Dilution (% Volume)	Soot (% Volume)	Viscosity at 100°C (cSt)	TBN (mg*KOH/g)
ULSD	80	< 1	< 0.1	10.8	5.83
50 PPM	105	< 1	0.1	15.3	4.59
100 PPM	201	< 1	0.1	15.1	4.20

After the ULSD runs and break-in period, the oil was changed with John Deere 15W-40 oil. This was the oil recommended by John Deere for use after the break-in period. After the 50 PPM runs, the engine oil had 108 hours of run time on it. This was below the recommended run time of 200 hours on an oil change, therefore only an oil sample was taken and sent off for analysis. This oil analysis came back with an abnormal concentration of water. This was probably due to improper sampling technique and contamination from the oil sampling suction pump being used for something else before this sample was drawn. Other abnormal levels of boron, magnesium, calcium and phosphorus were also present. All of those can be traced back to water contamination, wear metals, or improper oil being used [30] [31] [32]. They were all on the low side of abnormal, and the analysis suggested continuing use of the current oil with the suggestion to plot trends with future analysis to make sure it was only water contamination and not some other problem arising. The viscosity was 15.3 centistokes (cSt) at 100°C, which was above the minimum grade value for a 10W-40 oil, 12.5 cSt. The TBN was 4.59 cSt, which was just past the normal operating parameter of 50% of the starting TBN of 10.5

cSt for a 10W-40 oil. These parameters indicated that the oil was starting to wear out, but still fit for use.

After the 100 PPM runs, the engine oil had a total of 201 hours on it, which was a good point to take an oil sample since 200 hours is when John Deere recommends to change oil. With a different sampling technique than the 50 PPM analysis, the oil analysis showed no water contamination for this oil sample. However, the same abnormal metals that showed up with the 50 PPM sample were present in the 100 PPM oil sample, with the addition of copper. The analysis suggested that the copper was most likely from the oil cooler or EGR cooler. Like the 50 PPM sample, the level of these metals were on the low end of the abnormal stage, and again the suggestion was given to monitor these trends to see if any alternative action should take place. The viscosity went down to 15.1 cSt at 100°C, which was still above the 12.5 cSt minimum grade value for a 10W-40 oil. The TBN was 4.20 cSt, which was still within the normal operating parameters. The abnormal levels of the different metals is an interesting point, and a good topic for future study, but not a large enough abnormality to dictate the sulfur content of the fuel prematurely wearing out the oil. The viscosity and TBN numbers showed the oil's properties were still within usable parameters, and the sulfur content did not prematurely wear the oil out.

4. CONCLUSION

The tests that were conducted throughout this study tested the impact of fuel sulfur content on the operational characteristics of a Tier 4 Interim ULS diesel engine. This thesis concluded that for the operational parameters that this engine would see in a nuclear power plant as part of its emergency equipment, the maximum sulfur content tested of 100 PPM would have no detrimental consequences in the 72 hours that this engine would need to be run.

Throughout these tests, the engine was run on three different sulfur contents; ULSD, 50 PPM, and 100 PPM. At each of these sulfur contents, the engine was run at different engine loads; 30% for 12 hours, 90% for 12 hours, and 60% for 48 hours. For the 30% load condition, it was found that as sulfur content was increased, the exhaust temperatures increased as well, by 10-20°C. This caused the EGR temperatures to increase as well by 20°C, which increases the soot production, but not enough to change how the engine operated. The DPF soot load based on differential pressure at this engine load was inconclusive, because of the different times between regeneration. The fuel based soot loading started to show that it was not purely based on fuel usage and that all three fuel concentrations looked like they leveled off at the same mass concentration. The time-based soot loading showed that it was only based on the amount of run time of the engine, and in this loading condition was the factor that would cause the engine to go into regeneration, which is the desired result.

The 90% load condition showed the same increase in exhaust gas temperatures as the 30% condition did with respect to sulfur content. This could be due to the higher fuel usage allowing more sulfur to pass through the engine and deposit itself on the DOC and DPF. The EGR temperatures also showed the same trend as the 30% load, with the exception of the 50 PPM, which had a few degrees higher average temperature. The differential pressure soot loading for each of the sulfur concentrations at 90% load, showed the same rate of soot loading, 0.03g/hr-L. This was less than than the rate of soot loading for the time-based parameter was 0.06 g/hr-L. This means a regeneration will trigger on the time-based parameter before the differential pressure. An interesting find was the 50 PPM and 100 PPM fuel concentrations did cause an increase in engine coolant temperature, with the 100 PPM runs showing an oscillation in temperature. This could be due to the coolant fan coming on and off, but this point needs more investigation. And also like the 30% load, the fuel based soot loading parameter seemed to decrease from its initial starting value of 2.5 g/L-hr, then level off around 1.5 g/L-hr. This shows that this parameter must not only be based off of total fuel usage, but engine load as well.

The 60% load condition did not show the same trend with exhaust temperatures as the ULSD and 50 PPM fuels. In this concentration, the 100 PPM fuel had the lowest exhaust temperatures, followed by the USLD, then the 50 PPM fuel. The 60% load test also saw a regeneration occur, trigged off the time-based soot loading parameter, which was desired. The engine took load and ran normal as hoped and expected. The EGR temperatures were higher for each of the sulfur fuel concentrations, however temperature differences (5-10°C) weren’t as significant as the other load conditions produced (20-25°C). Like the other load conditions, the rate of increase of the differential based soot loading parameter was lower than the time-based soot loading rate, meaning the time-based soot loading would still trigger a regeneration first.

A few other points of interest for this test included the fact that the 100 PPM runs produced as much as a 10 HP difference between it and other two fuel concentration runs. This could have been contributed to the engine being down on power from the extra EGR being used, or the reaction between the engine dynamometer loading state and the engine's ECU output. Fuel pressure was also monitored but proved not to be an issue as there was no fuel pressure change in each of the loading conditions. The engine oil was also analyzed for wear metals, fuel dilution, soot acumination, viscosity change and TBN. From the analysis, it showed that fuel sulfur content did not show any noticeable changes to the characteristics of the engine oil, and following the manufacture oil change intervals should lead to optimal performance of the engine oil.

From all this it was determined that the sulfur content has little negative operational impact on the engine. It might have caused a loss of power in the 60%, 100 PPM test, however this could be mitigated in the field with increasing load or engine RPM. These tests also showed that the regeneration would be triggered on the time-based soot loading before any other parameter.

4.1 Future Research

The first test in future research could be to understand more about the power loss at the 60%, 100 PPM range. This would be considered the only point of worry from the results of this thesis. Another area that could be looked at would be to repeat these same tests with higher and/or different fuel sulfur concentrations. As there are some power plants that have up to 300 PPM sulfur in their fuel, it is recommended to use the same test procedures to test at least up to 300 PPM sulfur content. Another test that could be of use would be to see the long-term impact of the increased sulfur content on this and other engines. Increasing the amount of run time at the specified loads and sulfur concentrations would give a more realistic mode of operation for the real world (non-power plant) circumstances that these engines would be expected to operate without failure. This test's run time of 72 hours per sulfur concentration is how the power plants require these engines to operate, but they would run much more in the real world. One other area that could be studied is the increased EGR temperatures and possibly the fouling of the EGR cooler. This would be on concern regarding the emissions output of the engine, but if the cooler was fouled or plugged up enough, it could possibly impact the power output and other parameters of the engine.

BIBLIOGRAPHY

[1] Dallman, T., Menon, A., "Technology Pathways For Diesel Engines Used In Non-Road Vehicles And Equipment," September 2016, The International Council on Clean Transportation White Paper, 20160915.

[2] Ferguson, C.R., Kirkpatrick, A. T., *Internal Combustion Engines, Applied Thermoscience* 2nd Ed. Hoboken, NJ, John Wiley & Sons, Inc., 2001.

[3] U.S. Department of Energy. "Diesel Emission Control – Sulfur Effects (DECSE) Program; Phase 1 Interim Data Report No.4; Diesel Particulate Filters – Final Report." January 15, 2000.

[4] Nadkarni, R. A. K., "The Challenge of Sulfur Analysis in the Fuels of the Future," June 2004, *ASTM Standardization News*.

[5] Konig, A., Herding, G., Hupfeld, B., Richter, Th., Weidmann, K., "Current Tasks and Challenges for Exhaust Aftertreament Research. A Viewpoint from the Automotive Industry," 2001, Topics in Catalysis.

[6] John Deere. (2017) *003246.00 – DPF Outlet Temperature Extremely High – ctm 114619*. John Deere Service Advisor.

[7] Zheng, M., Reader, G. T., Hawley, J. G., "Diesel Engine Exhaust Gas Recirculation – A Review on Advanced and Novel Concepts," April 2004, *Energy Conversion and Management*, Vol 45.

[8] Kozak, M., Merkisz, J. "The Mechanics of Fuel Sulfur Influence on Exhaust Emissions from Diesel Engines," 2005, TEKA Kom. Mot. Energ. Roln., 5, 96-106

[9] John Deere. (2017) *Data Points Used in Service Advisor – ctm 114619*. John Deere Service Advisor.

[10] John Deere. (2017*) Calculated Soot Loading Rate of Change Abnormal – ctm114619.* John Deere Service Advisor.

[11] Faiz, A., Weaver, C. S., Walsh, M. P., *Air Pollution from Motor Vehicles: Standards and Technologies for Controlling Emissions*, World Bank Publications, 1996.

[12] Manufacturers of Emissions Controls Association. "The Impact of Gasoline Fuel Sulfur on Catalytic Emission Control Systems" September, 1998.

[13] Tan, P., Hu, Z., Lou, D., "Regulated and Unregulated Emissions from a Light-duty Diesel Engine with Different Sulfur Content Fuels," June 2009, *Fuel*, Vol. 68

[14] Lakshminarayanan, P. A., Nayak, N. S., *Critical Components Wear in Heavy Duty Engines*, John Wiley & Sons, 2011.

[15] Qianfan, X., *Diesel Engine System Design*, Woodhead Publishing, 2011.

[16] Kong, Y., Kozakiewicz, T., Johnson, R., Huffmeyer, C., "Active DPF Regeneration for 2007 Diesel Engines," SAE Technical Paper 2005-01-3509, 2005.

[17] Hoard, J., Abarham, M., Styles, D., Giuliano, J., "Diesel EGR Cooler Fouling," *SAE Int. J. Engines* 1(1):1234-1250, 2009.

[18] Mosburger, M., Fuschetto, J., Assanis, D., Filipi, Z., McKee, H., “Impact of High Sulfur Military JP-8 Fuel on Heavy Duty Diesel Engine EGR Cooler Condensate,” *SAE Int. J. Commer. Veh.* 1(1):100-107, 2009.

[19] ASTM D3120-08(2014), “Standard Test Method for Trace Quantities of Sulfur in Light Liquid Petroleum Hydrocarbons by Oxidative Microcoulometry”, ASTM International, West Conshohocken, PA, 2014, https://doi.org/10.1520/D3120-08R14

[20] ASTM D5453-16e1, “Standard Test Method for Determination of Total Sulfur in Light Hydrocarbons, Spark Ignition Engine Fuel, Diesel Engine Fuel, and Engine Oil by Ultraviolet Fluorescence”, ASTM International, West Conshohocken, PA, 2016, https://doi.org/10.1520/D5453-16E01

[21] Bielaczyc, P., Merkisz, J., Kozak, M., "Analysis of the Influence of Fuel Sulphur Content on Diesel Engine Particulate Emissions," SAE Technical Paper 2002-01-2219, 2002, doi:10.4271/2002-01-2219.

[22] Sutton, M., Stow C.. "Preliminary studies of the impact of diesel fuel sulphur on recommended oil service interval." *Ford Motor Company* (2004): 131-135.

[23] Zhang, J., He, K., Ge, Y., Shi, X., “Influence of fuel sulfur on the characterization of PM_{10} from a diesel engine,” March 2009, *Fuel*, Vol. 88.

[24] Diesel Fuel Standards and Rulemakings, https://www.epa.gov/diesel-fuel-standards/diesel-fuel-standards-and-rulemakings

[25] SAE Viscosity Grades http://www.viscopedia.com/viscosity-tables/substances/sae-viscosity-grades/

[26] What is Viscosity? http://www.kewengineering.co.uk/Auto_oils/oil_viscosity_explained.htm

[27] Oil Analysis User Guide, “Fluid Analysis Program”, Oil Analyzers Inc., August 2015, http://www.oaitesting.com/images/docs/Oil-Analyzers-User-Guide.pdf

[28] Arendt, A., “Oil Analysis – Making Sense of Used-Oil Reports,” Amsoil, March 2017.

[29] John Deere Plus-50 II Oils https://jdparts.deere.com/partsmkt/document/english/pmac/5565_fb_plus5015W40_0W40.htm#_Chemical_and_Physical_1

[30] Bob is the Oil Guy, “Engine Oil Analysis”, https://bobistheoilguy.com/engine-oil-analysis/

[31] Mayer, A., “4 Oil Analysis Test to Run on Every Sample”, *Practicing Oil Analysis*, March 2006.

[32] Evans, J. S., “Where Does All That Metal Come From?”, *Wear Check Africa*, 2010.