Great Lakes Maritime Research Institute

A University of Wisconsin - Superior and University of Minnesota Duluth Consortium

Shipboard Testing of B20

Final Report

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1 December 2008

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Research funded in part by the Great Lakes Maritime Research Institute.
This study was supported by the U.S. Maritime Administration
Grant # DTMA1-G-06-005

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Executive Summary

Main engine emissions and fuel consumption were monitored on the University of Minnesota Duluth (UMD) research vessel Blue Heron from 14 May 2008 to 30 October 2008. Two different primary fuels were used during the test period; no. 2 diesel and B20 (a mixture of 20% biodiesel and 80% diesel). The goals of the project were to determine the change in emissions and fuel consumption associated with switching from no. 2 diesel to B20 and to investigate any operational issues, including material compatibility, that are associated with the use of B20.

R/V Blue Heron, which is the test platform for the study, is an 86-foot-long former Grand Banks fishing trawler operated by the Large Lakes Observatory (LLO) at UMD. The diesel-powered systems on board include the main engine (CAT 3508 TA) and two generator sets (CAT 3304 and CAT C4.4 DITA). A data acquisition system and associated equipment were installed on the ship to continuously monitor and log the following parameters during main engine operation: main engine speed (RPM's), exhaust temperature, exhaust pressure, fuel consumption, and emissions (HC, CO, O_2, CO_2, NO_x). The fuel consumption for both generator sets is also monitored and recorded. Main engine speed, exhaust temperature, and exhaust pressure are recorded every 2 seconds, fuel consumption is recorded every 5 seconds, and the emissions are recorded in 30 second intervals.

Testing with no. 2 diesel occurred from 14 May 2008 to 20 July 2008. B20 was used as the primary fuel from 21 July 2008 to 30 October 2008. The Blue Heron has refueled with B20 three times, July 21, August 25, and September 22, taking on about 2000 to 2500 gallons during each refueling. The refueling process for the Blue Heron is complicated by the fact that B20 is not readily available locally. The B20 is mixed at the refinery while it is being loaded into a large tanker truck. The B20 is then transferred from the large tanker truck to a small tanker truck for final delivery to the Blue Heron at the pier. The additional steps in the refueling process increase the likelihood of contamination of the fuel.

Data available in the literature for dynamometer tests conducted with on-road diesel engines using B20 shows a decrease in unburned hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) emissions, and a slight increase in oxides of nitrogen (NO_x) emissions when compared to no. 2 diesel. Dynamometer tests are conducted under controlled conditions and generally consist of two types; constant speed with a varying load, and constant load with a varying speed. Neither of these two tests can be recreated onboard a ship that is underway. Thus, a direct comparison between the on-road engine tests from the literature and the current test is problematic. The data presented in the current study was analyzed based on main engine speed. The main engine speed is related to, but is not equivalent to, the load on the engine. There are other factors that cause variations in the load on the main engine at a given speed such as current, sea state, and wind velocity. No attempt was made to separate out the effect of these additional factors on the data. The data was time-averaged over periods when the main engine was operated at constant speed. These periods ranged from 10 minutes to several hours.

The data for main engine fuel consumption and oxides of nitrogen (NO_x), oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), and unburned hydrocarbons (HC) emissions were analyzed as a function of main engine speed in revolutions-per-minute (RPM). A majority of the

data points fell within two speed ranges; 400 to 700 RPM and 1000 to 1400 RPM. The lower operating speeds are consistent with cruising and "trolling" during research operations and the higher speeds are consistent with high-speed transit at, or near, full throttle. General trends observed in the data include the following:

- B20 and diesel usually exhibited similar fuel consumption rates, as expected.
- Some of the higher RPM data points indicated a higher rate of fuel consumption for B20 when compared to diesel. These higher readings for B20 are believed to be caused by clogging of the fuel filter, which can cause higher readings from the fuel log systems.
- Soundings taken of the fuel tank and a review of the amount of fuel taken onboard during refueling indicated a similar rate of fuel consumption for B20 and diesel.
- NO_x, O_2, CO, and CO_2 emissions were similar for both B20 and no. 2 diesel use at the same engine speed.
- All of the emissions data were consistent with expected trends for diesel engine operations.
- HC emissions are expected to be very small for a diesel engine operating at a constant engine speed. The emissions analyzer employed in the current study only registered HC emissions during evolutions involving rapid and large changes in engine speed. The inability to measure any HC emissions at steady operating conditions may be due to instrument accuracy (which for HC emissions is less than 400 ppm), instrument response time, or the location of the emissions probe.

One of the goals for the current study was to investigate any operational issues involved with the use of B20. No material compatibility issues were observed over the period July 21 to October 30 when B20 was used as the primary fuel. However, there was a significant decrease in the operational lifetime of the primary fuel filter when using B20. The Blue Heron uses a 2-micron Racor filter as its primary fuel filter. The filter is replaced when the fuel pressure drops to below 50 psi when the engine is at full throttle. When no. 2 diesel is used, the first fuel filter installed after refueling sometimes exhibits a shortened lifetime, on the order of hours. This has been attributed to contaminated fuel in the past. Subsequent fuel filters have typical lifetimes from 100 to 200 hours. The use of B20 resulted in a very short fuel filter lifetime (on the order of hours) for the first fuel filter installed after refueling, with filter lifetime gradually increasing for each subsequent filter. In some cases, the filter lifetime eventually increased to 100 to 200 hours. Several factors may contribute to the observed behavior, including, but not limited to, "cleaning" of the fuel system by the biodiesel component in B20, the use of a fine (2-micron) primary fuel filter, and the complicated refueling process employed for B20 which may have resulted in contamination of the fuel.

The data acquisition system employed in the present study will allow for continued monitoring of emissions and fuel consumption on the Blue Heron. Two issues that have been noted are the inability to measure HC emissions (except during engine transients) and the reduction in filter lifetime observed when using B20. Future work will focus on resolving these issues.

1. Introduction

Extensive testing of on-road diesel engines using varying percentages of biodiesel has shown a decrease in most emissions when compared to no. 2 diesel fuel [1]. Test results have shown a marked decrease in the emission of unburned hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM), and a slight increase in oxides of nitrogen (NO_x) emissions when B100 is used as a fuel. In addition, B100 does not contain sulfur, and therefore the burning of B100 does not contribute to acid rain. These beneficial emissions are obtained with no noticeable loss in performance [1]. However, completely replacing diesel fuel with B100 in all diesel engines is impractical given the current rate of diesel consumption. Biodiesel is best utilized in a blend with regular diesel fuel, extending current fuel supplies and reducing our dependence on imported oil. A B20 blend still produces significantly lower emissions than diesel fuel [1] and does not suffer from the material compatibility issues associated with higher percentage blends [2].

The available data suggests that the use of biodiesel blends in shipboard diesel-powered systems offers several attractive advantages: it reduces overall emissions, it reduces engine wear through increased lubricity, and it reduces the consumption of petroleum. Tests using on-road diesel engines suggest that no engine modifications are required to utilize blends of up to 20% biodiesel (B20). Legislative and industrial efforts also point to the use of blends up to B20 for both on-road and off-road applications in the near future.

There are currently very few studies addressing the use of biodiesel blends on ships. The National Oceanic and Atmospheric Administration's (NOAA) Great Lakes Environmental Research Laboratory (GLERL) has recently completed the conversion of three research vessels to operate using B100 [3]. The issues involved with converting the ships, the methods of measuring emissions, and the actual emissions data from the GLERL project appear to be unpublished. Studies that utilized B20 in vessels have been carried out in Washington State [4] and Canada [5]. Detailed data is not available for either of these cases. The study in Washington [4] was actually suspended due to the clogging of fuel filters.

The current project consists of a shipboard test of B20. Testing was performed in collaboration with Large Lakes Observatory (LLO) at the University of Minnesota Duluth (UMD), which operates the research vessel (R/V) Blue Heron. The vessel was operated using both diesel and B20. Fuel consumption and emissions of unburned hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and oxides of nitrogen (NO_x) were monitored over a period of approximately six months. Periodic monitoring of fuel lines and seals were also conducted during the use of B20 to check for leakage and material compatibility issues. The specific goals of the project were two-fold; determine the change in emissions and fuel consumption for the test ship under various operating conditions when the fuel is changed from diesel to B20, and determine if there are any material compatibility and/or operational issues associated with the use of B20 on the test vessel.

1.1 Project Description

The R/V Blue Heron, which is shown in Figure 1, was used as a test bed to study fuel consumption and emissions when B20 and diesel fuel are used as the primary fuels. Periodic inspections of the vessel's equipment and reviews of the engineering logs were also performed to check for an operational or material compatibility issues associated with the use of B20.

Figure 1: R/V Blue Heron

GLMRI awarded separate funds towards the operation of UMD's research vessel, the Blue Heron, in support of the current project. Dr. Ricketts and the R/V Blue Heron's participation in this project consisted of the following: 1) procurement and installation of flow meters to measure fuel consumption rate, 2) installation of emissions monitoring equipment, 3) use of standard diesel during the first half of the R/V Blue Heron's cruise season, 4) use of B20 during the second half of the Blue Heron's cruise season, 5) operation and monitoring of the data acquisition equipment, 6) periodic inspection of fuel lines and fitting for leaks, and 7) providing summaries of relevant engineering logs.

The project costs associated with the R/V Blue Heron can be divided into three categories: 1) equipment and materials for the project, 2) salary for personnel involved in the project, and 3) fuel costs. Equipment and materials for the project consisted of fuel flow meters for the R/V Blue Heron's main engine and two generators as well as hoses, fittings, steel, fuel filters and miscellaneous pieces of hardware for the project. The flow meters were placed in the fuel lines for the main engine and generators and cables were run from the sensors forward to the bosun's locker. Probes were installed in the ship's exhaust stack to measure exhaust temperature, exhaust pressure, and emissions. Cables were also run from these sensors forward to the bosun's locker. A work station was constructed in the bosun's locker to house a computer and other electronics associated with the project. Salary costs associated with the Blue Heron included the time that ship's personnel needed to install and monitor the equipment. Dr. Ricketts' participation in the project was not charged to GLMRI and is considered matching funds from

the University. Fuel costs included refueling the Blue Heron twice with diesel and three times with B20 during the course of the project.

Data for the vessel's emissions and fuel consumption were gathered when operating with 2 different fuels: diesel, and B20. A data acquisition system and computer were used to record all measured values for later analysis. In addition, when B20 was used, fuel lines and hoses were periodically inspected for leaks to identify any potential material compatibility issues. A review of the engineering logs was also conducted to determine any operational issues associated with the use of B20 as compared to diesel.

A commercially available flue gas analyzer was used to measure the main engine emissions on the Blue Heron. Emissions measurements consisted of unburned hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and oxides of nitrogen (NO_x). The exhaust temperature and pressure at the sampling point were also taken. HC emissions did not register during steady-state operation of the main engine and were therefore not included in the final discussion of results.

The data was classified based on main engine speed. Fuel consumption and emissions data obtained using different fuels tend to group in two ranges of engine speeds based on the mode of operation for the ship. The lower engine speeds in revolutions-per-minute (RPM) corresponded to maneuvering (entering and exiting port) and research operations, while the higher RPM's indicate high speed transit at, or near, full throttle.

Portions of the results presented in this report were incorporated in a presentation given at the GLMRI University Affiliates Meeting held in Duluth, MN on September 26th, 2008. The initial results were also submitted in October 2008 for publication in the Great Lakes/Seaway Review. A seminar for the faculty and students in the Department of Mechanical and Industrial Engineering at the University of Minnesota Duluth is also planned for December 1st, 2008.

2. Measurements and Methodology

The diesel-powered systems on board the R/V Blue Heron include the main engine (CAT 3508 TA, Fig. 2) and two generator sets (CAT 3304 TA and CAT C4.4 DITA). Fuel log systems manufactured by FloScan Instrument Company, Inc., were used to monitor fuel consumption. Each of the three engines required its own fuel log system which consisted of a forward flow meter, a return flow meter, and a fuel flow gauge. The model numbers for the fuel log systems used on the Blue Heron are as follows:

- CAT 3508 TA (Main Engine) – FloScan 860TL-236-2K Fuel Log System
- CAT 3304 TA (Generator) – FloScan 850L-201-2K Fuel Log System
- CAT C4.4 DITA (Generator) – FloScan 850L-201-2K Fuel Log System

A pulse signal output from each of the systems was used as an input to a data acquisition system.

A data acquisition system and associated equipment were installed on the ship to continuously monitor and log the main engine speed (RPM's), exhaust temperature, exhaust pressure, fuel consumption, and emissions (HC, CO, O_2, CO_2, NO_x). The fuel consumption for both generator sets was also monitored and recorded. Main engine speed, exhaust temperature, and exhaust pressure where recorded every 2 seconds, fuel consumption was recorded every 5 seconds, and the emissions where recorded in 30 second intervals. A Testo 350-XL flue gas analyzer (shown in Figure 2) was used to monitor emissions.

Figure 2: Test 350-XL flue gas analyzer

A dataTaker® DT 80 data logger was used to gather the data for fuel consumption, exhaust temperature, exhaust pressure, and main engine speed. A detailed list of the inputs and outputs for the DT 80 is given in Appendix C. Software provided with the data logger allowed for programming of the DT 80 and real-time monitoring of the inputs through a USB connection. Figure 3 shows the engineer's station in the bosun's locker. The computer monitor displays the

real-time measurements of the DT 80 and the three gauges below the monitor display the fuel flow rates for the three engines. The data logger software was also used to download the measurements to comma-separated-variable (.csv) files that could be imported into Microsoft® Excel®. The Testo 350-XL flue gas analyzer was also connected to the computer via a serial cable. A program add-in for Microsoft® Excel® that came with the analyzer allowed for control of the emissions monitoring and importation of the data into Excel®.

Figure 3: Engineer's station in bosun's locker of Blue Heron. Computer monitor displays the real-time measurements from the data acquisition system using dial indicators. Three gauges for monitoring the fuel consumption of the main engine and the two generators are located below the monitor.

Testing with no. 2 diesel occurred from 14 May 2008 to 20 July 2008. B20 was used as the primary fuel from 21 July 2008 to 30 October 2008. The Blue Heron refueled with B20 three times, July 21, August 25, and September 22, taking on about 2000 to 2500 gallons during each refueling. The refueling process for the Blue Heron is complicated by the fact that B20 is not readily available locally. The B20 was mixed at the refinery while it was being loaded into a large tanker truck. The B20 was then transferred from the large tanker truck to a small tanker truck for final delivery to the Blue Heron at the pier. The additional steps in the refueling process increase the likelihood of contamination of the fuel.

3. Results

The on-road engine test results discussed in the Introduction were conducted under controlled conditions using a dynamometer to vary the load on the engine. Dynamometer tests generally consist of two types, constant speed with a varying load, and constant load with a varying speed. Neither of these two types of tests can be recreated aboard a ship while it is operating. Thus, a direct comparison between the on-road engine tests from the literature and the current test is problematic. The data obtained in the current study has been plotted versus main engine speed. The main engine speed of the ship is related to, but is not equivalent to, the load on the engine. There are other factors that cause increases, decreases, and variations in the load on the main engine at a given speed such as current, sea state, and wind velocity. No attempt has been made to separate the effect of these additional factors from the data. The data presented here has been time-averaged over periods when the main engine was operated at constant speed. These periods ranged from about 10 minutes to several hours.

3.1 Fuel Consumption

Figure 4 shows the main engine fuel consumption in gallons per hour (GPH) as a function of main engine speed in RPM's for no. 2 diesel and B20. The grouping of data points in the 400 to 700 RPM range is consistent with cruising and "trolling" during research operations conducted on the Blue Heron. The higher RPM's are consistent with high-speed transit at, or near, full throttle. B20 and diesel exhibit similar fuel consumption rates at the lower engine speeds, as expected. The difference in fuel consumption at higher engine speeds for some of the data points is believed to be caused by clogging of the fuel filter, which can cause higher readings from the fuel log systems. Soundings taken of the fuel tank and a review of the fuel taken onboard during refueling indicate a similar rate of fuel consumption for B20 and diesel.

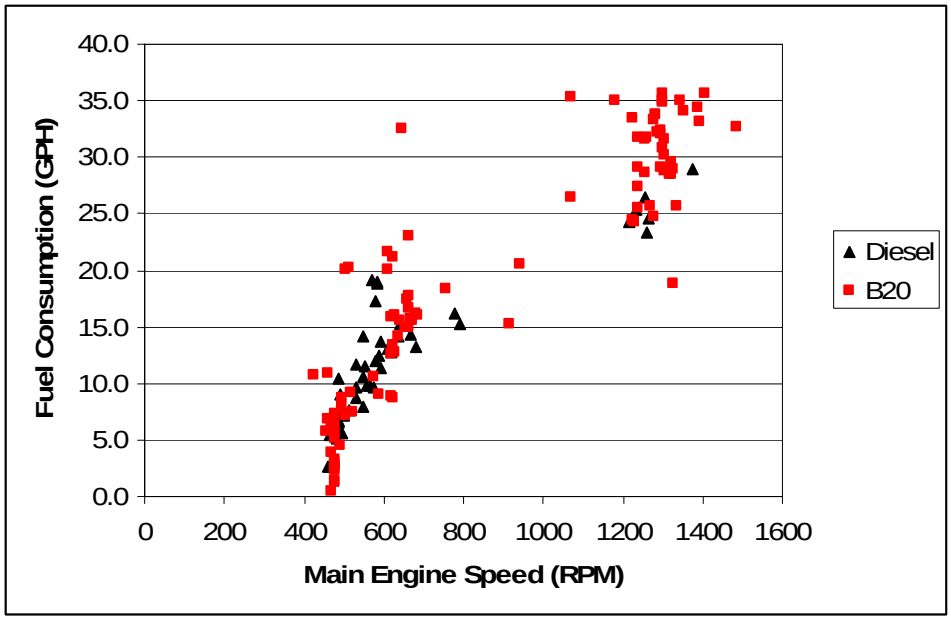

Figure 4: Main engine fuel consumption versus speed

3.2 Exhaust Temperature

Figure 5 shows the main engine exhaust temperature in degrees Celsius as a function of main engine speed in RPM's for no. 2 diesel and B20. The exhaust temperature increases almost linearly from about 150°C at 500 RPM to 450°C at 1400 RPM. Exhaust temperatures using diesel and B20 are almost identical. This variation of exhaust temperatures is expected since diesel engines operate at very lean air-to-fuel ratios at lower load (lower engine RPM), and the air-to-fuel ratio decreases as the load is increased (engine RPM increased). The decrease in the air-to-fuel ratio with increasing engine RPM's leads to less excess air and thus a higher exhaust temperature.

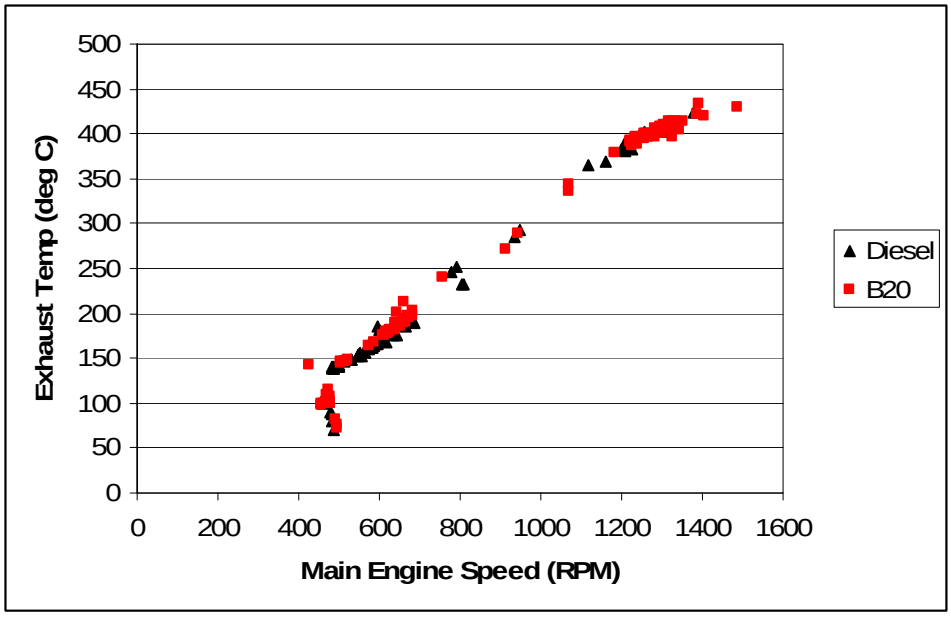

Figure 5: Main engine exhaust temperature versus speed

3.3 Emissions

Figure 6 shows the percent oxygen (O_2) in the main engine exhaust as a function of main engine speed for no. 2 diesel and B20. The oxygen concentration decreases with an increase in RPM as expected. The reason for this behavior was already presented in the discussion for the exhaust temperature shown in Figure 5. The diesel engine operates closer to stoichiometric at higher load (higher RPM) resulting in less excess air and thus less excess oxygen.

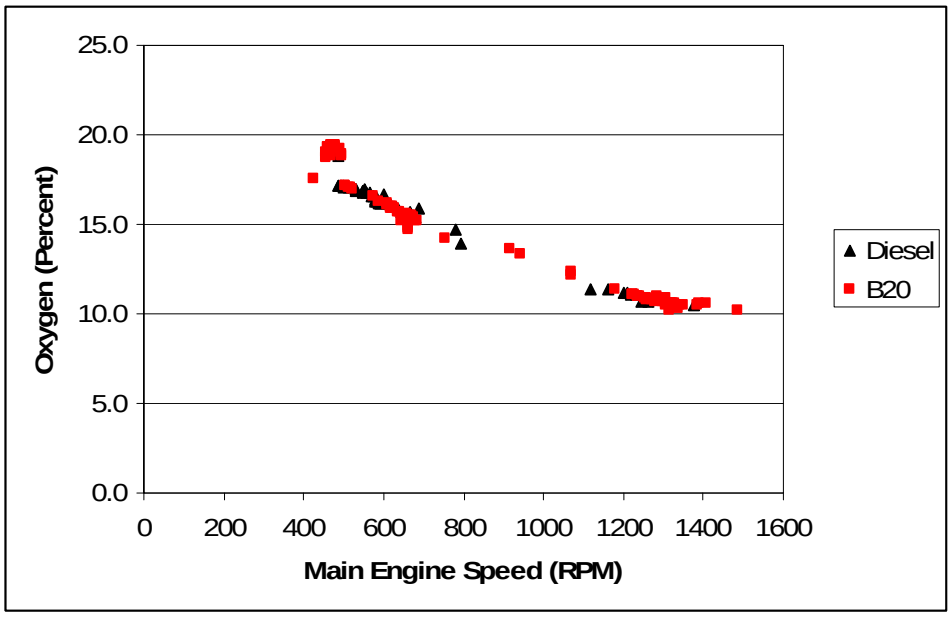

Figure 6: Percent oxygen in main engine exhaust versus speed

Figure 7 shows the parts-per-million (ppm) carbon monoxide (CO) concentration in the main engine exhaust as a function of main engine speed for no. 2 diesel and B20. The results for B20 and diesel are similar, but there is significant scatter in the data and no identifiable trend. Maximum concentrations are on the order of 1000 ppm with the majority of the data is in the 0 to 500 ppm range. These are very low CO concentrations that are consistent with the lean operating conditions present in diesel engines. The scatter is most likely due to the accuracy and sensitivity of the emissions monitoring device employed in this study. The dynamometer tests discussed in the Introduction predict a slight decrease in CO emissions when using B20 as compared to diesel. The results in Figure 7 neither confirm nor contradict the cited conclusion.

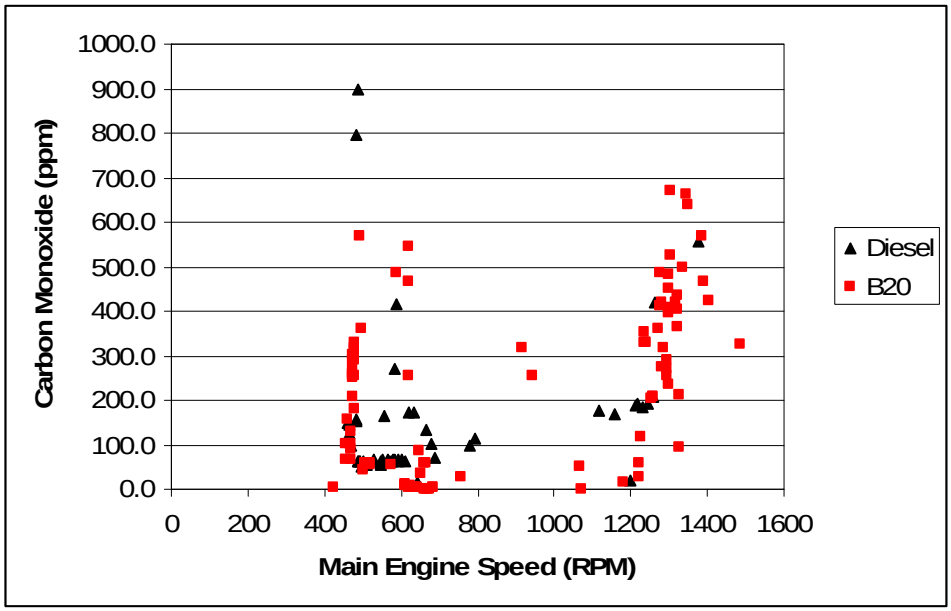

Figure 7: Carbon monoxide (CO) emissions versus engine speed

Figure 8 shows the percent carbon dioxide (CO_2) in the main engine exhaust as a function of main engine speed for no. 2 diesel and B20. The almost linear increase in percent carbon dioxide with RPM's is expected since the diesel engine operates "less" lean at higher RPM's. Carbon dioxide emissions are approximately the same for the two fuels.

Figure 9 shows the emissions of oxides of nitrogen (NO_x) in parts-per-million (ppm) as a function of main engine speed. The emissions are similar for both fuels at lower engine speeds. The higher NO_x emissions in some of the data points for B20 at the higher speeds appear to be consistent with that fuel's tendency to produce more NO_x as noted in the Introduction. However, it may also be caused by a higher load on the shaft. As previously discussed, several external factors can affect the engine load at a given speed, and a higher engine load would tend to increase emissions. The general trend of increasing NO_x emissions with increasing RPM (engine load) is expected because of lower air-to-fuel ratios and thus higher in-cylinder temperatures at higher loads (engine RPM's).

Unburned hydrocarbon (HC) emissions are expected to be very small for a diesel engines operating at a constant engine speed because they always operate lean. The emissions analyzer employed in the current study only registered HC emissions during evolutions involving rapid and large changes in engine speed. Thus, no data for HC emissions is presented in this report. The inability to measure any HC emissions at steady operating conditions may be due to instrument accuracy (which for HC emissions is less than 400 ppm), instrument response time, or the location of the emissions probe.

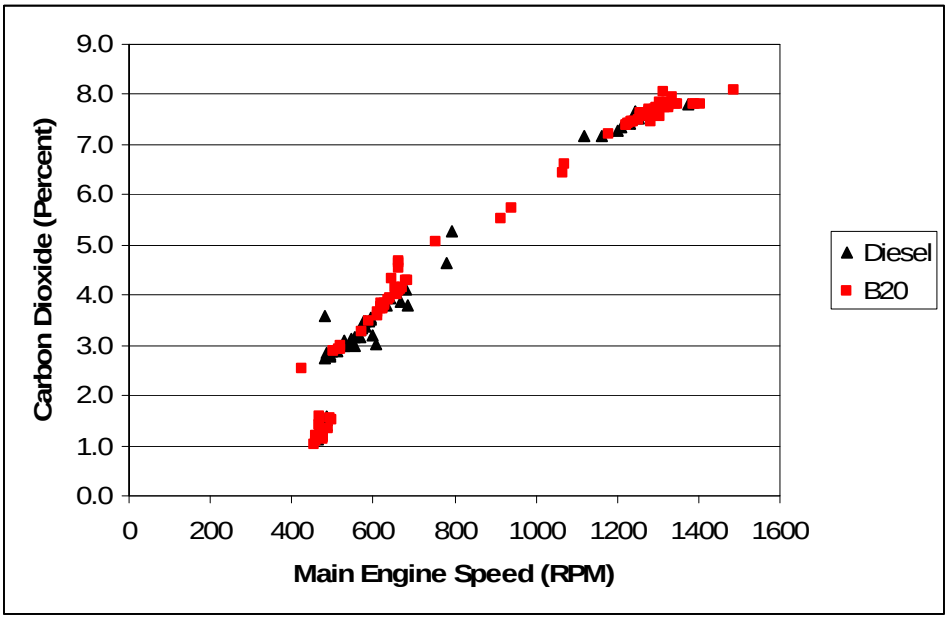

Figure 8: Carbon dioxide (CO_2) emissions versus engine speed

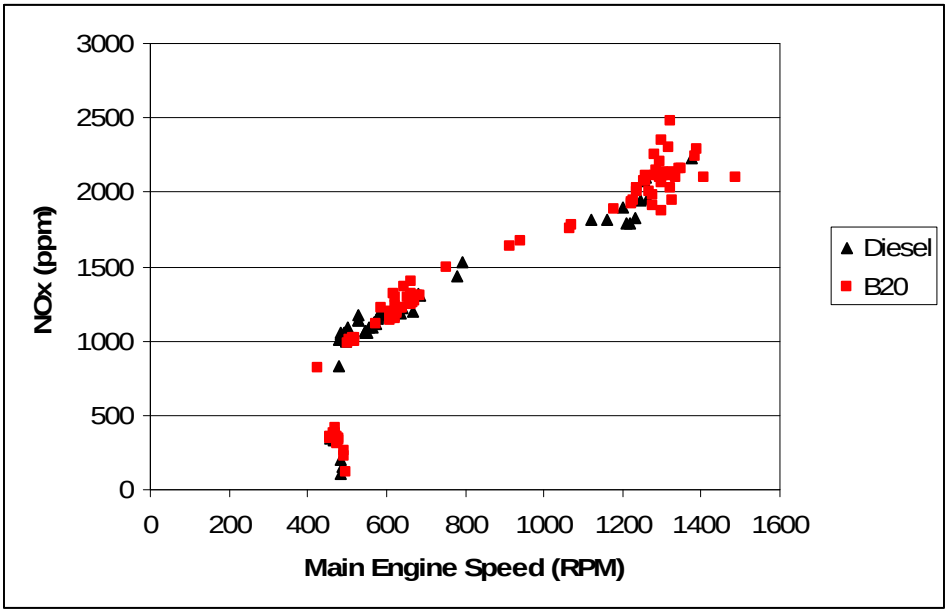

Figure 9: Oxides of nitrogen (NO_x) emissions versus main engine speed

3.4 Operational Issues

One of the goals for the current study was to investigate any operational issues involved with the use of B20. No material compatibility issues were observed over the period July 21 to October 30 when B20 was used as the primary fuel. However, there was a significant decrease in the operational lifetime of the primary fuel filter when using B20. The Blue Heron uses a 2-micron Racor filter as its primary fuel filter. The filter is replaced when the fuel pressure drops to below 50 psi when the engine is at full throttle. When no. 2 diesel is used, the first fuel filter installed after refueling sometimes exhibits a shortened lifetime, on the order of hours. Subsequent fuel filters have typical lifetimes from 100 to 200 hours. This has been attributed to contaminated fuel in the past. The use of B20 on the Blue Heron has resulted in a significant decrease in the fuel filter lifetime, with filter lifetime increasing for each subsequent filter. Figure 10 shows the filter lifetimes for each filter used after a given refueling with B20. The last two filters used after the 21 July refueling (Fig. 10, black solid line) have lifetimes similar to those obtained with diesel fuel. The fuel filter lifetime decreased significantly after refueling with B20 on August 25 (red dashed line) and September 22 (green dash-dot line). Several factors may contribute to the observed behavior, including, but not limited to, “cleaning” of the fuel system by the biodiesel component in B20, the use of a fine (2-micron) fuel filter, and the complicated refueling process employed for B20 which may have resulted in contamination of the fuel.

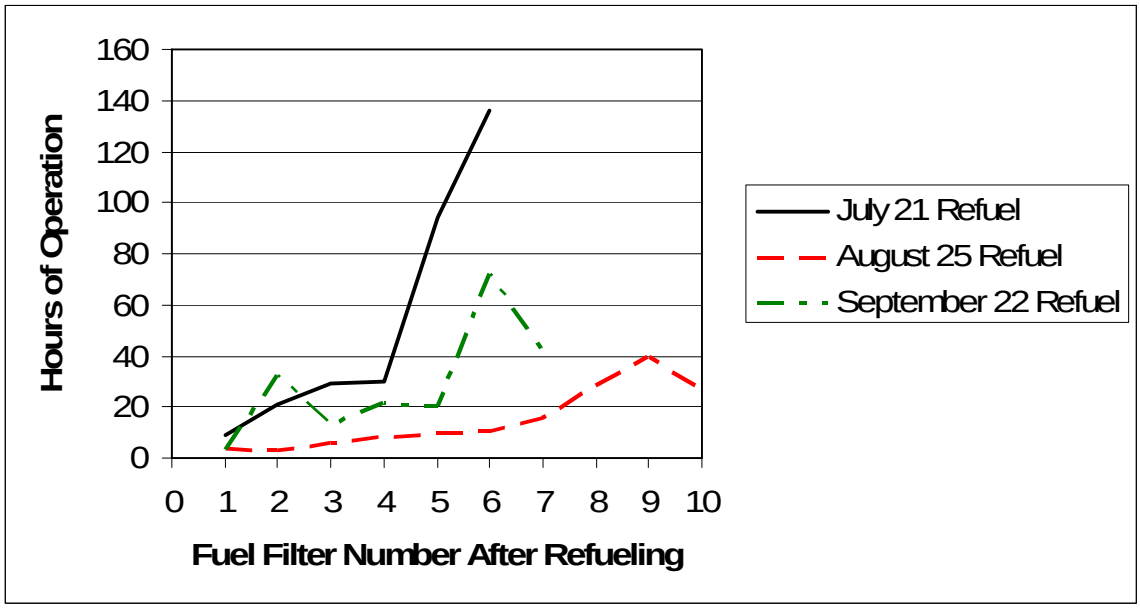

Figure 10: Primary fuel filter lifetime after refueling with B20.

4. Conclusions and Recommendations

A data acquisition system was employed to continuously monitor and record data for main engine fuel consumption, exhaust temperature, and oxides of nitrogen (NO_x), oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), and unburned hydrocarbons (HC) emissions. An analysis of the data as a function of main engine speed (RPM) suggests the following:

- At the same RPM, B20 and diesel exhibited a similar rate of fuel consumption, as expected.
- Some of the higher RPM data points indicated a higher rate of fuel consumption for B20 when compared to diesel. The slightly higher readings for B20 are believed to be caused by clogging of the fuel filter, which can cause higher readings from the fuel log systems.
- Soundings taken of the fuel tank and a review of the fuel taken onboard during refueling indicate a similar rate of fuel consumption for B20 and diesel.
- The emissions data was consistent with expected results for a normally operating diesel engine.
- NO_x, O_2, CO, and CO_2 emissions are similar for B20 and no. 2 diesel use at the same engine speed.
- NO_x emissions at high engine speeds may be slightly higher when using B20. However, the slight differences may be caused by external factors that affect the engine load such as sea state and currents.
- The emissions analyzer did not register HC emissions during steady operating conditions and only registered non-zero values during evolutions involving rapid and large changes in engine speed. This behavior may be result from the instrument accuracy, the instrument response time, or the location of the emissions probe.

No material compatibility problems were observed during the three months when B20 was used as the primary fuel. The use of B20 did however cause a significant decrease in the operational lifetime of the primary fuel filter. This is particularly noticeable immediately after refueling with B20; the first fuel filter installed after refueling exhibited a filter lifetime of less than 10 hours.

The data acquisition system employed in the present study will allow for continued monitoring of emissions and fuel consumption on the Blue Heron. Two issues that have been noted are the inability to measure HC emissions (except during engine transients) and the reduction in filter lifetime observed when using B20. Future work will focus on resolving these issues.

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Appendix A

Main Engine Fuel Flow Rate, Main Engine Exhaust Temperature, and Emissions Data

Diesel Data

Time		ME Speed	ME Flow Rate	Emissions				Exhaust
				O2	CO	NOx	CO2	Temp
From	To	RPM	GPH	%	ppm	ppm	%	deg C
5/13/2008 23:43	5/14/2008 4:13	1319						403
5/14/2008 6:11	5/14/2008 8:56	1319						405
5/14/2008 10:14	5/14/2008 10:43	1208						381
5/14/2008 20:45	5/14/2008 22:12	809						231
5/14/2008 22:49	5/15/2008 1:26	806						232
5/15/2008 3:30	5/15/2008 5:55	933						285
5/21/2008 2:06	5/21/2008 4:25	478						91
5/21/2008 7:00	5/21/2008 8:43	481						89
5/21/2008 19:03	5/21/2008 23:53	474						101
5/22/2008 1:07	5/22/2008 7:19	473						102
5/23/2008 0:00	5/23/2008 4:28	947						294
5/23/2008 5:51	5/23/2008 7:29	459						102
5/23/2008 8:23	5/23/2008 12:22	1301						410
5/29/2008 0:00	5/29/2008 0:50	596						186
5/29/2008 1:36	5/29/2008 3:12	455						102
5/29/2008 6:37	5/29/2008 12:28	617						177
5/29/2008 22:18	5/29/2008 23:28	654						189
5/30/2008 0:23	5/30/2008 2:13	636						185
5/30/2008 2:56	5/30/2008 4:57	658						193
5/30/2008 7:34	5/30/2008 8:33	676						199
5/30/2008 11:54	5/30/2008 13:33	1225						382
6/14/2008 4:59	6/14/2008 6:03	1211		11.1	186.7	1791	7.4	391
6/14/2008 11:37	6/14/2008 17:10	1244		10.7	192.2	1942	7.7	398
6/16/2008 8:27	6/16/2008 9:18	484		19.1	797.7	207	1.4	79
6/16/2008 9:42	6/16/2008 10:08	1200		11.2	20.7	1901	7.3	382
6/16/2008 10:13	6/16/2008 10:18	1119		11.4	177.4	1813	7.2	364
6/16/2008 10:27	6/16/2008 10:36	600		16.7	67.6	1179	3.2	181
6/16/2008 10:47	6/16/2008 11:34	686		15.9	69.3	1305	3.8	190
6/16/2008 11:39	6/16/2008 11:48	470		19.1	99.0	377	1.3	109
6/16/2008 12:48	6/16/2008 13:36	1160		11.4	169.1	1817	7.2	369
6/22/2008 0:00	6/22/2008 3:48	529	9.6	16.9	65.8	1169	3.0	148
6/22/2008 4:28	6/22/2008 7:29	501	7.6	17.1	63.6	1090	2.9	142
6/22/2008 8:41	6/22/2008 8:56	486	6.7	17.2	64.6	1051	2.8	139
6/22/2008 10:52	6/22/2008 12:37	530	8.7	16.8	63.5	1138	3.1	148
6/22/2008 13:02	6/22/2008 13:26	486	6.6	17.1	62.0	1046	2.8	140
6/22/2008 22:46	6/23/2008 3:42	495	5.6	17.1	62.0	1052	2.8	141
6/23/2008 5:11	6/23/2008 6:05	487	6.7	19.0	899.6	159	1.5	139
6/23/2008 8:29	6/23/2008 10:12	481	5.2	19.3	154.7	829	2.7	140
6/23/2008 11:33	6/23/2008 12:50	482	5.9	19.2	155.4	1005	3.6	139
6/23/2008 22:02	6/24/2008 6:32	498	7.2	17.1	51.6	995	2.9	142

Diesel Data

Time		ME Speed	ME Flow Rate	Emissions				Exhaust
				O2	CO	NOx	CO2	Temp
From	To	RPM	GPH	%	ppm	ppm	%	deg C
6/24/2008 7:05	6/24/2008 11:40	512	7.6	17.1	53.8	1004	2.9	146
6/24/2008 21:04	6/24/2008 22:11	578	17.2	16.3	63.8	1168	3.5	163
6/24/2008 22:48	6/25/2008 0:21	493	9.0	17.2	63.3	1052	2.8	142
6/25/2008 0:58	6/25/2008 1:58	583	19.1	16.3	64.9	1187	3.5	162
6/25/2008 3:19	6/25/2008 3:59	582	18.9	16.4	269.4	1171	3.4	162
6/25/2008 5:06	6/25/2008 5:33	529	11.6	17.0	63.4	1136	3.0	149
6/25/2008 6:00	6/25/2008 8:50	548	14.2	16.8	58.1	1066	3.1	155
6/25/2008 10:11	6/25/2008 10:50	464	5.4	19.2	126.5	361	1.3	101
6/26/2008 10:44	6/26/2008 13:52	570	19.1	16.6	61.9	1127	3.3	164
6/28/2008 5:38	6/28/2008 5:59	1376	29.0	10.5	558.3	2227	7.8	424
6/28/2008 6:21	6/28/2008 7:23	1259	23.3	10.8	207.4	2094	7.6	399
6/28/2008 8:15	6/28/2008 10:05	555	9.8	16.7	162.8	1092	3.2	153
6/28/2008 12:56	6/28/2008 14:43	609	13.0	16.2	61.7	1166	3.0	173
6/28/2008 16:18	6/28/2008 17:57	680	13.3	15.4	101.0	1319	4.1	195
6/29/2008 1:07	6/29/2008 9:38	1262	24.6	10.7	420.1	1959	7.6	397
6/29/2008 11:46	6/29/2008 12:33	459	2.6	19.3	149.1	339	1.2	99
6/29/2008 13:46	6/29/2008 14:36	1255	26.5	10.9	206.0	2077	7.5	402
7/9/2008 8:27	7/9/2008 9:56	593	11.4	16.2	66.1	1196	3.5	167
7/9/2008 10:25	7/9/2008 11:04	574	9.7	16.5	63.8	1118	3.3	161
7/9/2008 13:59	7/9/2008 16:35	549	10.6	16.9	63.0	1060	3.0	155
7/9/2008 17:23	7/9/2008 18:40	577	12.0	16.4	65.0	1155	3.4	162
7/9/2008 19:50	7/9/2008 20:27	546	7.9	16.8	54.0	1071	3.1	153
7/10/2008 20:22	7/10/2008 20:57	566	9.9	16.7	65.8	1086	3.2	157
7/10/2008 22:08	7/10/2008 22:44	642	15.2	15.7	14.2	1222	3.9	176
7/10/2008 23:57	7/11/2008 1:40	779	16.2	14.7	96.3	1432	4.6	245
7/11/2008 2:10	7/11/2008 3:18	792	15.3	13.9	114.5	1528	5.3	251
7/11/2008 4:59	7/11/2008 7:08	619	12.8	16.0	172.0	1179	3.8	168
7/16/2008 3:36	7/16/2008 5:35	588	12.5	16.2	415.0	1206	3.5	164
7/16/2008 6:12	7/16/2008 7:01	635	14.2	15.9	172.3	1190	3.8	175
7/16/2008 8:36	7/16/2008 9:10	666	14.3	15.7	135.0	1197	3.9	185
7/16/2008 13:40	7/16/2008 14:17	594	13.7	16.2	64.6	1185	3.6	166
7/18/2008 8:41	7/18/2008 9:00	485	10.5	18.8	1341.9	109	1.6	69
7/18/2008 10:18	7/18/2008 11:12	553	11.5	17.0	67.8	1053	3.0	157
7/18/2008 11:31	7/18/2008 12:28	1217	24.3	11.1	191.1	1785	7.4	388
7/18/2008 12:49	7/18/2008 14:16	465	2.7	19.4	143.7	329	1.1	103
7/18/2008 14:37	7/18/2008 15:44	1232	25.4	11.0	183.4	1829	7.4	396

B20 Data

Time		ME Speed	ME Flow Rate	Emissions				Exhaust Temp
From	To	RPM	GPH	O2 %	CO ppm	NOx ppm	CO2 %	deg C
7/23/2008 23:05	7/24/2008 0:02	646	32.5	15.2	85.9	1365	4.3	201
7/24/2008 0:41	7/24/2008 2:02	461	11.0	19.3	158.5	338	1.2	100
7/24/2008 3:30	7/24/2008 4:44	505	20.1	17.1	59.4	1009	2.9	146
7/24/2008 5:10	7/24/2008 6:08	515	20.2	17.1	58.1	1024	2.9	147
7/24/2008 6:42	7/24/2008 10:15	519	9.1	17.1	58.2	998	2.9	147
7/24/2008 10:52	7/24/2008 10:59	574	10.5	16.6	53.8	1117	3.3	163
7/24/2008 11:21	7/24/2008 12:46	521	7.5	17.0	54.1	1026	3.0	149
7/24/2008 21:55	7/25/2008 0:53	502	7.2	17.1	43.8	981	2.9	145
7/25/2008 2:06	7/25/2008 2:50	663	17.8	14.7	57.5	1400	4.7	212
7/25/2008 7:29	7/25/2008 10:57	1327	18.8	10.6	94.8	1948	7.7	414
7/30/2008 22:18	7/30/2008 23:02	1223	33.5	11.1	26.6	1920	7.4	392
7/30/2008 23:20	7/30/2008 23:48	1180	35.1	11.3	14.9	1882	7.2	380
7/31/2008 0:18	7/31/2008 1:25	1071	35.3	12.1	0.0	1775	6.6	343
7/31/2008 1:52	7/31/2008 3:00	470	6.8	19.4	102.0	358	1.2	101
7/31/2008 4:25	7/31/2008 8:11	456	5.8	18.7	100.0	343	1.0	98
7/31/2008 8:54	7/31/2008 12:09	458	6.9	19.0	65.0	350	1.1	99
7/31/2008 22:59	8/1/2008 5:00	1294	29.0	10.8	272.1	2100	7.7	408
8/1/2008 5:45	8/1/2008 7:02	470	6.1	19.0	91.2	382	1.4	100
8/1/2008 7:36	8/1/2008 10:29	1255	28.6	10.9	205.4	2081	7.5	401
8/15/2008 21:27	8/16/2008 10:20	611	20.1	16.1	10.3	1194	3.6	175
8/16/2008 10:25	8/16/2008 10:30	425	10.8	17.6	3.1	821	2.5	142
8/16/2008 10:32	8/16/2008 10:43	470	6.9	18.8	67.5	414	1.6	110
8/16/2008 22:41	8/17/2008 5:54	610	21.7	16.1	8.5	1144	3.6	176
8/17/2008 6:23	8/17/2008 9:52	664	23.0	15.5	0.2	1245	4.1	194
8/17/2008 11:07	8/17/2008 12:52	624	21.2	16.0	6.0	1154	3.7	180
8/18/2008 0:20	8/18/2008 4:11	681	16.2	15.2	2.4	1300	4.3	204
8/18/2008 4:42	8/18/2008 6:06	618	12.7	16.0	3.2	1176	3.7	179
8/18/2008 7:14	8/18/2008 8:43	641	15.6	15.7	4.5	1225	3.9	189
8/18/2008 9:39	8/18/2008 10:23	659	17.4	15.6	0.2	1246	4.0	194
8/18/2008 10:35	8/18/2008 12:49	624	13.4	15.9	3.4	1190	3.7	181
8/18/2008 13:51	8/18/2008 14:06	755	18.4	14.2	26.5	1498	5.0	240
8/18/2008 14:17	8/18/2008 15:04	1237	25.6	11.0	331.2	2001	7.4	396
8/20/2008 20:33	8/20/2008 21:00	621	15.9	15.9	254.9	1235	3.8	177
8/20/2008 22:13	8/20/2008 23:13	673	15.6	15.4	1.2	1269	4.2	195
8/21/2008 1:00	8/21/2008 2:13	662	14.9	14.9	58.3	1309	4.5	190
8/21/2008 4:07	8/21/2008 5:20	663	16.7	14.8	57.8	1322	4.6	191
8/21/2008 6:57	8/21/2008 9:54	627	12.8	15.8	4.1	1200	3.8	180

B20 Data

Time		ME Speed	ME Flow Rate	Emissions				Exhaust Temp
From	To	RPM	GPH	O2 %	CO ppm	NOx ppm	CO2 %	deg C
8/22/2008 3:38	8/22/2008 4:45	654	15.0	15.4	34.5	1293	4.1	185
8/22/2008 6:03	8/22/2008 7:57	638	14.1	15.7	4.4	1219	3.9	181
8/22/2008 8:30	8/22/2008 9:24	685	16.0	15.2	4.3	1306	4.3	197
8/22/2008 9:49	8/22/2008 10:31	627	16.0	15.9	4.6	1188	3.8	181
8/22/2008 12:25	8/22/2008 13:09	669	15.8	15.5	0.6	1256	4.1	196
8/22/2008 15:37	8/22/2008 16:41	1391	33.1	10.5	467.1	2284	7.8	433
9/4/2008 3:29	9/4/2008 4:45	1295	32.1	10.8	255.2	2211	7.7	405
9/4/2008 9:28	9/4/2008 14:45	1320	28.5	10.6	405.7	2297	7.8	412
9/4/2008 16:00	9/4/2008 16:22	467	4.0	19.0	103.9	383	1.4	100
9/5/2008 6:39	9/5/2008 11:57	1260	31.7	10.8	208.3	2113	7.6	401
9/5/2008 12:58	9/5/2008 17:34	1281	33.8	10.7	274.3	2106	7.7	406
9/5/2008 18:07	9/5/2008 18:43	1486	32.7	10.2	324.2	2097	8.1	430
9/11/2008 11:04	9/11/2008 11:54	1257	31.6	10.9	206.5	2074	7.5	395
9/11/2008 15:55	9/11/2008 16:33	1238	31.7	11.0	329.3	2031	7.5	389
9/13/2008 7:06	9/13/2008 7:32	497	8.7	18.9	1206.1	122	1.5	73
9/13/2008 8:20	9/13/2008 8:46	1294	32.4	10.8	291.3	2121	7.7	400
9/13/2008 11:10	9/13/2008 11:52	1278	33.3	10.8	486.7	1904	7.6	401
9/13/2008 13:15	9/13/2008 13:52	476	7.2	19.4	180.2	317	1.2	108
9/13/2008 14:33	9/13/2008 15:32	1298	35.1	10.7	395.9	1874	7.7	405
9/17/2008 21:55	9/18/2008 3:34	1279	24.8	10.7	412.4	1975	7.6	398
9/18/2008 7:31	9/18/2008 9:54	1227	24.3	11.1	118.5	1944	7.4	386
9/20/2008 6:48	9/20/2008 7:19	495	8.0	18.9	359.5	259	1.6	76
9/20/2008 8:05	9/20/2008 8:33	1270	25.7	10.8	361.4	1998	7.6	396
9/20/2008 10:27	9/20/2008 11:01	1350	34.1	10.5	639.9	2157	7.8	414
9/20/2008 11:46	9/20/2008 12:53	1239	29.1	11.0	328.4	2026	7.5	388
9/21/2008 8:03	9/21/2008 9:10	492	4.5	19.2	570.0	225	1.3	81
9/21/2008 10:09	9/21/2008 10:42	914	15.2	13.6	316.2	1642	5.5	272
9/21/2008 11:24	9/21/2008 11:45	476	5.8	19.4	257.3	330	1.2	114
9/21/2008 13:15	9/21/2008 13:43	1068	26.4	12.4	50.6	1753	6.4	336
9/21/2008 14:07	9/21/2008 14:30	943	20.5	13.3	253.0	1668	5.7	289
9/23/2008 14:27	9/23/2008 17:32	1306	28.8	10.6	526.9	2120	7.7	409
9/23/2008 21:51	9/23/2008 22:52	476	5.6	19.4	251.4	329	1.2	100
9/24/2008 0:46	9/24/2008 2:41	1386	34.4	10.5	567.9	2239	7.8	423
9/25/2008 15:12	9/25/2008 17:38	477	2.4	19.4	292.6	333	1.2	101
9/25/2008 18:31	9/25/2008 21:00	476	2.7	19.4	255.0	327	1.2	100
9/25/2008 22:55	9/26/2008 0:45	476	2.7	19.4	270.7	329	1.2	100

B20 Data

Time		ME Speed	ME Flow Rate	Emissions				Exhaust Temp
From	To	RPM	GPH	O2 %	CO ppm	NOx ppm	CO2 %	deg C
9/26/2008 1:47	9/26/2008 4:16	1301	30.9	10.7	449.3	2116	7.7	407
9/26/2008 5:24	9/26/2008 7:02	1301	34.9	10.7	480.7	2058	7.7	405
9/26/2008 8:13	9/26/2008 9:25	1287	32.1	10.8	316.9	2149	7.6	402
9/26/2008 10:50	9/26/2008 14:28	1223	24.5	11.1	59.4	1928	7.4	390
10/1/2008 8:14	10/1/2008 9:00	1305	31.6	10.9	669.1	2133	7.6	403
10/1/2008 9:35	10/1/2008 10:26	475	5.2	19.4	209.1	348	1.1	105
10/1/2008 10:43	10/1/2008 11:27	1283	33.7	11.0	419.2	2258	7.5	397
10/8/2008 7:28	10/8/2008 7:47	1343	35.0	10.5	664.1	2163	7.8	404
10/8/2008 12:23	10/8/2008 15:00	475	6.3	19.3	288.8	331	1.2	101
10/8/2008 17:02	10/8/2008 17:25	1336	25.6	10.3	498.8	2098	8.0	414
10/10/2008 9:40	10/10/2008 11:30	477	2.3	19.4	290.6	330	1.2	101
10/10/2008 13:07	10/10/2008 14:56	475	1.2	19.3	301.3	334	1.2	100
10/10/2008 18:32	10/10/2008 19:30	1305	30.1	10.5	408.4	2109	7.9	410
10/12/2008 7:25	10/12/2008 8:11	1315	28.5	10.2	420.2	2107	8.0	414
10/12/2008 12:33	10/12/2008 13:32	478	2.6	19.3	331.1	332	1.2	101
10/13/2008 8:19	10/13/2008 9:26	1320	29.6	10.6	362.9	2027	7.7	410
10/13/2008 12:26	10/13/2008 13:36	477	1.3	19.4	253.6	306	1.2	99
10/13/2008 18:04	10/13/2008 19:11	1405	35.7	10.5	421.8	2103	7.8	420
10/14/2008 10:56	10/14/2008 12:38	477	3.1	19.4	316.0	351	1.2	101
10/14/2008 13:29	10/14/2008 16:30	478	3.3	19.3	308.6	347	1.2	102
10/14/2008 17:35	10/14/2008 18:34	1237	27.4	11.0	354.9	2007	7.5	397
10/24/2008 2:41	10/24/2008 10:02	589	9.0	16.3	485.0	1226	3.5	167
10/24/2008 11:37	10/24/2008 16:07	621	8.7	15.9	543.2	1295	3.8	178
10/24/2008 17:59	10/25/2008 2:02	618	8.9	15.8	467.1	1314	3.8	180
10/25/2008 3:39	10/25/2008 7:45	1320	29.2	10.5	434.2	2476	7.8	408
10/28/2008 7:40	10/28/2008 8:21	1325	29.0	10.6	213.6	2133	7.8	396
10/28/2008 8:48	10/28/2008 10:14	467	0.5	19.4	130.2	348	1.2	101
10/28/2008 10:27	10/28/2008 11:23	1298	35.7	10.7	234.5	2345	7.7	401

Appendix B

Fuel Filter Change Log

Fuel Filter Change Log

Refuel		Filter Change		Approx. Time on Used Filter	Remarks	
Date	Fuel Type	Date	Time	(hrs)		
		5/6/2008	1603	unknown	Filter from last season, > 100 hrs	
		5/22/2008	2110	118		
6/17/2008	Diesel					
		6/23/2008	1146	199.7		Filter
		6/27/2008	2018	104		Number
		7/18/2008	1022	216		After
7/21/2008	B20				New Filter	Refueling
		7/23/2008	900	9	1st filter change after refueling	1
		7/24/2008	614	21		2
		7/25/2008	1050	29		3
		7/31/2008	1015	30		4
		8/9/2008	200	94		5
		8/17/2008	1309	136		6
8/25/2008	B20					
		8/28/2008	1430	125.5	Filter carried over from previous refueling	
		8/28/2008	1842	4	1st filter change after refueling	1
		8/28/2008	2200	3		2
		8/29/2008	400	6		3
		8/29/2008	1238	8.5		4
		9/3/2008	1057	9.5		5
		9/3/2008	2124	10.5		6
		9/4/2008	1333	16		7
		9/5/2008	1802	28.5		8
		9/16/2008	1913	39.5		9
		9/17/2008	2123	26		10
9/22/2008	B20					
		9/23/2008	1100	32	Filter carried over from previous refueling	
		9/23/2008	1400	3	1st filter change after refueling	1
		9/24/2008	2200	32		2
		9/25/2008	1124	12.5		3
		9/26/2008	919	21.5		4
		10/8/2008	1649	20.5		5
		10/23/2008	2343	72		6
		10/30/2008	1311	42		7

Appendix C

Data Logger Inputs and Outputs

Measurement	Sensor	DT 80 Channel	Signal Type	Output Units
Main Engine Exhaust Temperature	Omega TJ36-CASS-18U-12 Thermocouple	Analog 1	Temperature (K-type thermocouple)	degrees Celsius
Main Engine Exhaust Pressure	Omega PX219-030GI Pressure Transducer	Analog 2	Current (4 to 20 mA)	PSIG
Main Engine Speed	Monarch ROS-W Remote Optical Sensor	Analog 3	Frequency	RPM
Main Engine Fuel Flow	FloScan 860TL-236-2K Fuel Log System	Digital 2	Counter (10,000 pulses/gallon)	GPH
CAT 3304 TA Generator Fuel Flow	FloScan 850L-201-2K Fuel Log System	Digital 3	Counter (10,000 pulses/gallon)	GPH
CAT C4.4 DITA Generator Fuel Flow	FloScan 850L-201-2K Fuel Log System	Digital 4	Counter (10,000 pulses/gallon)	GPH