M/V OSKI

EMISSIONS TESTS

BIO-DIESEL & INLET AIR WATER INJECTION

FINAL REPORT TO MARAD

PREPARED BY WALTHER ENGINEERING

ON BEHALF OF THE S.F. BAY WTA

UTILIZING A BLUE & GOLD FLEET VESSEL

JUNE 26, 2002

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M/V OSKI Emissions Testing June 26, 2002

Executive Summary

The M/V OSKI, a passenger only 12 knot ferry operated by Blue & Gold Fleet on San Francisco Bay, California, was tested for diesel engine emissions from August, 2001 until April, 2002 to determine the levels of engine emissions using normal off road diesel, 0.05% sulfur diesel, 20% and 100% soybean based biofuel. The tests were conducted on the starboard main engine underway, with and without water injection into the air inlet stream. At the conclusion of the waterborne tests a dynamometer test was conducted on the starboard engine, which had been recently removed and replaced with a low NOx engine.

The following results were observed for engine operation at nearly full power. Partial RPMs produced similar results at a rate proportional to the percent of RPM except that CO was inversely proportional.

Assuming off road diesel as a basis counted in grams per hour:
NOx increased 24 % with 100% biofuel.
NOx increased 11% with 20% biofuel blend.
NOx decreased 26% with water injection.
Water injection decreased 100% biofuel N0x by 12%.
Fuel rates changed so slightly between fuels as to be indistinguishable.
Sulfur production was a function of the sulfur in the fuel. Biofuel is reported to contain a very small amount. The diesel had less than half a hundredth of a %.
CO emissions were very low.
CO_2 emissions did not change with fuel change.
Biofuel produces oxygen during plant growth production via photosynthesis.
Biofuel reduces particulates by about one half.
The engine did show signs of light rust from water injection originally but did not show obvious signs of distress at the end of the test when viewed through the air ports. Some cylinder deposit cleaning was expected. A longer test run and more thorough teardown inspection would be required to determine the full effects.
Lube oil sample analysis showed deterioration of TBN and increased wear metals.

Respectfully submitted,
Charlie Walther

I. Introduction

Internal combustion engines operating on a diesel cycle and using diesel fuel are in use throughout the world primarily for land and sea transportation, major power production, and small-scale power generation. The diesel cycle offers advantages over the gasoline engine cycle (Otto cycle) in terms of power production and efficiency. However, due to the nature of combustion in a diesel cycle and properties of the diesel fuel itself, these engines are prone to produce high levels of pollutants in their exhaust.

The species of pollutants of greatest environmental concern are CO, NO_x and SO_x, which are regulated as criteria pollutants, and particles which are also regulated as criteria pollutants in the PM_{10} and $PM_{2.5}$ standards. Due to the nature of the combustion process, hydrocarbons (HCs) are not a major source of pollution from diesel engines. Diesel engines produce significantly higher NO_x emissions than Otto-cycle engines. The refining process to produce gasoline for Otto-cycle engines removes nearly all sulfur from the fuel, but this is not the case with diesel fuel and thus the remaining sulfur in the fuel is converted to SO_2 in the exhaust stream. And due to the nature of the combustion process, high levels of particulate matter (usually in the form of soot, but also in the form of soluble organic compounds, ultrafine oil particles, or sulfate particles from condensing SO_2 emissions) are released from diesel engines.

A testing project is presented below which investigates the effect on the four primary pollutants discussed above of replacing standard off-road diesel fuel (an EPA low-sulfur formulation) with blended bio-diesel/diesel fuel or 100% bio-diesel fuel, in a diesel engine aboard a Blue & Gold Fleet ferry vessel operating in the San Francisco Bay. The bio-diesel fuel consists primarily of processed and refined vegetable oils such as soybean oil. This fuel type is attracting attention in that it is a renewable fuel, and this testing will investigate what effects this fuel has on the emissions characterization of the diesel engine tested aboard the Blue & Gold Fleet vessel. Chemical analyses of both the standard off-road diesel fuel and the bio-diesel fuel used are provided in Appendices B & C. Additionally, a water injection system is tested with all fuel types, and at high and low pressure injection with 100% diesel fuel. Water injection is a technology aimed at reducing emissions of NOx from engines by injection of finely atomized water droplets

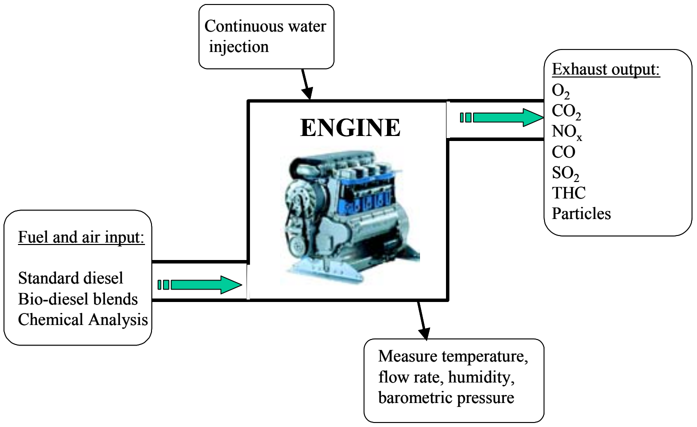


Figure 1. Schematic of engine and measurement system

into the air intake of a diesel engine, thereby reducing the overall combustion temperature. The water injection system was designed to operate at an RPM of 1200 or greater. The water injection system consists of a pressure pump, accumulator, filter, water softener, pressure regulator, and a discharge line connected to solenoids and then to fine sprayers or the bilge drain. A switch on the engine throttle activates the "spray on" valve at a predetermined throttle setting. Water is sprayed at either 60 psi (low pressure injection) or 85 psi (high pressure injection) into the air inlet to the blower and mixed with intake air. When the throttle is lowered to the set switch point, the spray valve is closed and the drain dump valve is opened to spill the water remaining in the spray line so as to avoid water and hydraulic damage to the engine internals at shutdown.

After testing, oil sample analysis showed increased wear metals and oil TBN degradation. Both engines were not deemed suitable for rebuild. These engines were over normal maintenance rebuild hours prior to these tests. The generator engines ran on the same fuels but without water injection. Generator oil samples were normal. See Appendix E for an attached lube oil analysis.

The report below summarizes diesel engine gas emissions tests conducted on August 3, 2001, September 4, 2001, October 31, 2001, December 6, 2001 and March 7, 2002 aboard the Blue & Gold Fleet vessel Oski, operating in the San Francisco Bay, as well as four emissions tests conducted on April 26, 2002 on the Oski engine mounted on a water-brake dynamometer. The aim of this testing was to provide a baseline from which to compare the effects of bio-diesel blends and pure bio-diesel fuel, as well as to begin to explore the potential emissions impact of the water injection system. The following report provides an overview of the methodology and instrumentation used, as well as presenting results, analysis, and conclusions from all tests conducted. Figure 1 shows a diagram of the system and the testing inputs and outputs.

II. Methodology

Seven emissions tests were conducted on board the Blue & Gold Fleet vessel Oski, and four additional emissions tests were conducted on the Oski engine operating on a water-brake dynamometer. The vessel was equipped with two identical Detroit Diesel engines at port and starboard. Specifications of the engines are summarized below in Table 1. Both engines were equipped with a 7.9in diameter exhaust duct which vented on the outer hull of the vessel at the waterline. All tests aboard the vessel Oski were conducted by probing the exhaust duct at a point along the duct approximately 6ft. from the starboard engine. The duct was tapped in a direction perpendicular to the exhaust gas flow direction. The tap was a simple tee with a machined radius on the interior side of the duct, in order to prevent disturbance of the exhaust gas flow. All measurement devices were inserted perpendicular to the flow direction through the tap. For testing conducted on the water-brake dynamometer, gas emissions measurements were conducted at a point in the ducting approximately 3ft from the engine, and similarly all measurement devices were inserted perpendicular to the flow direction.

ENGINE SPECIFICATIONS	
Detroit Diesel 12V-71NA-7122-7000	
Number of Cylinders	12
Bore & Stroke – in	4.25 x 5.00
Displacement – in^3	852
Compression Ratio	18.7:1
Combustion System	Direct Injection
Aspiration	Natural
Power Output – bhp	360 (at 1800r/min)
BMEP – lb/in^2	93.1

Table 1. Specifications of the Detroit Diesel engine model 12V-71NA-7122-7000

Instrumentation

Exhaust gas composition was measured by using the Enerac ® Model 3000 portable emissions analyzer manufactured by Energy Efficiency Systems of Westbury, NY. The emissions analyzer was equipped with a hand-held probe. The probe was comprised of a 12in long, 0.38in diameter heated sampling tube. The tip of the tube ended in a 1in long, 0.315in diameter sintered metal filter, designed to remove particulate matter from the gas stream. The probe body contained a small sample pump to draw sample gas through the probe tip and to deliver the sample gas at a prescribed flow rate to the sensors. The probe body also contained a silica-crystal drying chamber to remove water vapor from the gas sample. The emissions analyzer was equipped with four sensors: an O_2 sensor; an electrochemical NO/NO_2 sensor; an electrochemical CO sensor; and an electrochemical SO_2 sensor. The concentration of CO_2 and total hydrocarbons (THC) was calculated by the emissions analyzer. Data acquisition from the emissions analyzer was conducted by a laptop computer, using an RS-232 serial instrument connection, and running the LabView ® data acquisition software.

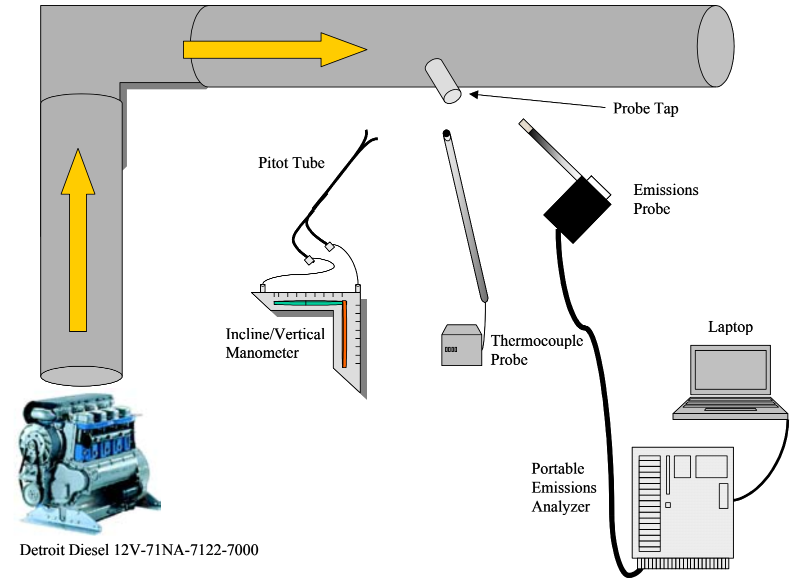


Figure. 2. Schematic of testing instrumentation

Exhaust gas velocity in the exhaust duct was measured by use of a pitot tube. The pitot tube was an S-type Dwyer Instruments pitot tube with a high pressure and a low pressure inlet. The tubing material was 316 stainless steel, with a tubing diameter of 5/16in. The high pressure and low pressure outlets from the pitot tube were connected by hosing to a combination incline-vertical manometer. The manometer used a red oil of specific gravity 0.856, capable of measuring a pressure range of 0 – 6.00in H_2O, in gradations of 0.05in H_2O. The manometer was affixed to the interior wall of the vessel to maintain horizontal alignment during testing.

Exhaust gas temperature was measured by use of a thermocouple probe. The probe was a 1/4in diameter 316 stainless steel tube sheathing a glass-fiber braid reinforced standard type-K thermocouple. The thermocouple bead was located inside the tubing approximately 1/2in from the end of the tube, in order to shield the thermocouple from thermal radiation effects. The thermocouple signal was measured by a hand-held digital thermocouple reader. A schematic of the gas emissions testing instrumentation is shown in Figure 2.

Testing Protocol

A total of eleven tests were conducted using the standard off-road diesel fuel, using a blend of 20%/80% bio-diesel fuel and standard diesel fuel by mass, using 100% bio-diesel fuel, using 100% bio-diesel fuel with a water injection system installed on the engine, and using standard off-road diesel fuel with the water injection at high and low pressures. For each fuel type, the testing consisted of varying the RPM of the engine from a minimum of approximately 600RPM to a maximum of approximately 1700RPM. This RPM range spanned the minimum-to-maximum engine speeds encountered in typical usage. In all cases, no passengers were aboard the vessel other than basic crew and testing personnel, thus it was not possible to simulate the load condition of a full passenger complement. The expected load conditions of the vessel were used to determine load settings on the dynamometer for the final emissions tests conducted. Before measurements were taken for each test, the system was allowed to reach a steady state. Steady-state conditions were determined by thermocouple and manometer measurements, and were typically several minutes at each RPM. In all test cases an insulation blanket was used to seal the tap around the probe, minimizing exhaust gas leakage through the sampling tap.

Velocity measurements were made for each RPM at steady-state conditions. The pitot tube probe was inserted with the high-pressure inlet facing the flow direction, and the low-pressure inlet facing opposite the flow direction. It was observed that once steady-state conditions were reached, minimal fluctuation in manometer pressure occurred, and no time-varying change in manometer pressure occurred. This is consistent with a hydrodynamically fully developed flow, which was expected at a large distance along the exhaust duct from the engine. The velocity probe traversed the diameter of the exhaust duct, and measurements were taken at six radial positions evenly spaced 1.2in apart along the centerline of the exhaust duct.

Temperature measurements were taken at the centerpoint of the exhaust duct for each test. A traverse across the exhaust duct diameter for each test determined that there was minimal temperature variation in the radial direction. This is consistent with a thermally fully developed flow.

Emissions measurements were taken at the centerpoint of the exhaust duct for each test with the standard diesel fuel, and at three evenly spaced radial positions 2.63” apart with the blended fuel. The traverse across the exhaust duct diameter during the testing with blended fuel resulted in a variation of species concentrations in the radial direction that was less than 1% of the centerpoint reading. This is consistent with a well-mixed flow, and an error well below the instrument error of the Enerac. In all tests, emissions data were acquired over a minimum 2-minute period, to account for any turbulent fluctuation in the species concentrations. All species were measured simultaneously by the emissions analyzer.

Particulate emissions levels were measured by making use of a flow-aligned particulate probe inserted into the probe tap. The probe consisted of a 3in length 1/4in diameter stainless steel probe placed in the centerline of the exhaust duct. The particulate probe was connected in-line with a quartz particulate filter and a vacuum pump drawing the sample through a stainless steel ball rotameter. The rotameter valve was kept fully open, thus the rotameter acted strictly as a flow-measuring device without providing flow control. Flow rate was set by the vacuum pump and any pressure drop across the system. The rotameter was used as a means of monitoring the actual flow rate across the filter, which provides a means of correcting data at varying RPM and fuel type so that comparison can be made. The filter was allowed to accumulate particulate matter for a given period of time, typically 15min. Particulate mass measurements are made by comparing the filter weight before and after insertion into the exhaust stream. This method is not capable of distinguishing particle size distribution, but will give an indication of total particulate mass production rates in the exhaust stream, allowing for comparison of the particulate production for each of the fuel types tested and the water injection system. A schematic of the particle measurement system is shown in Figure 3.

As shown in Figure 3, the exhaust was drawn across the filter by use of a 1/3 horsepower vacuum pump. The dual sealed chamber design of the pump prevented any contamination of the exhaust stream with pump oil or other residue. A shut-off valve provided a means for regulating flow times.

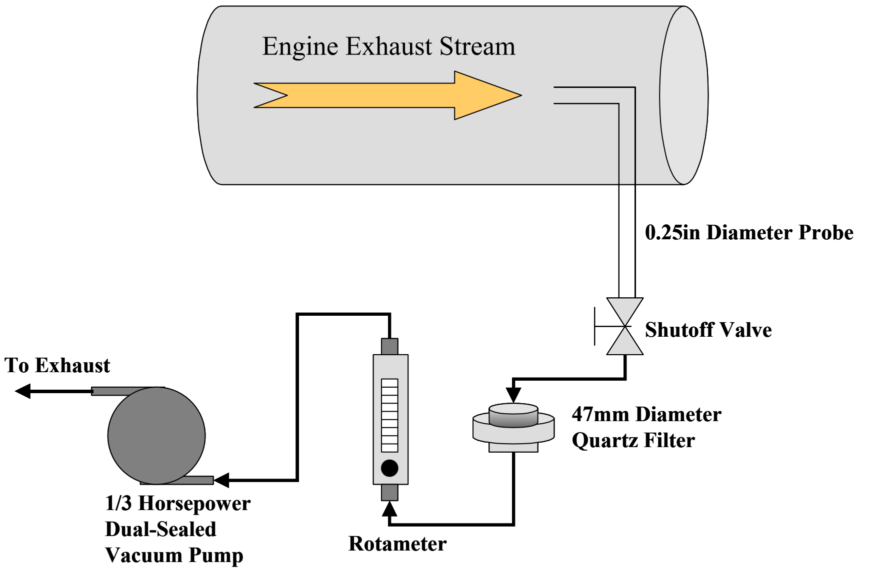


Figure 3 A schematic of the particle collection system

III. Analysis and Results

Emission results are presented in three methods. For ease of comparison between various fuel types and the water injection system, gas-phase emissions data needs only to be in concentration form, since differences in mass flow rates between various fuel types are not significant. Secondly, to analyze the impact of these gas-phase emissions, results must also be presented for emissions production rates on a gram per hour basis. This second method makes use of pitot tube and thermocouple measurements to calculate a mass flow rate and thereby calculate the mass production rate of pollutants. Finally the third method reports the particle measurements on a mass production rate basis.

Concentration Format Results

Results are presented below for concentrations of pollutants in the exhaust stream as a function of the engine RPM. It should be noted that pollutant concentrations are, in

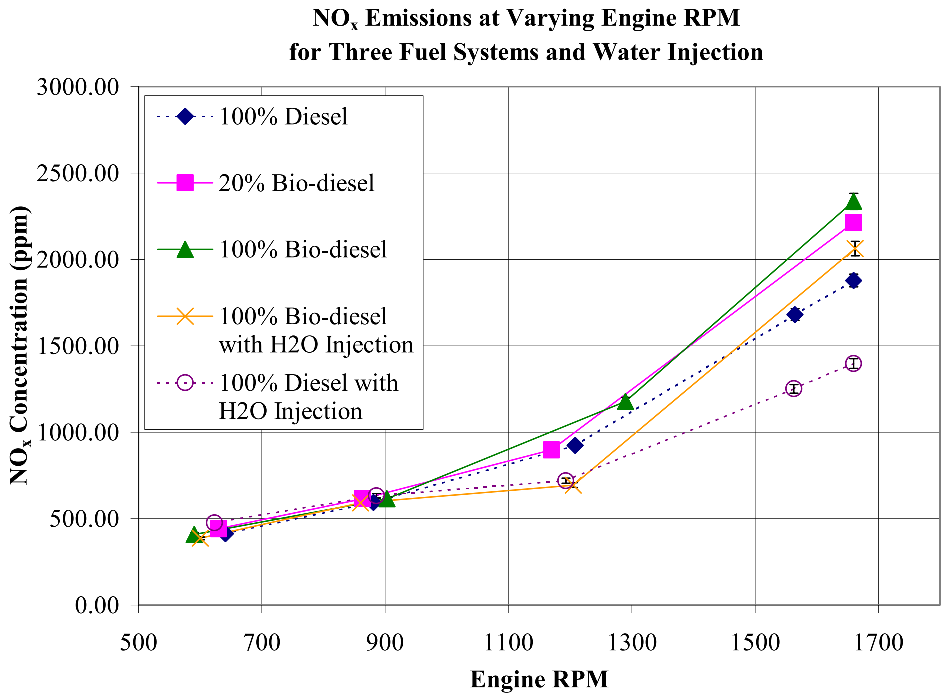


Fig. 4 NOx emissions at varying engine RPM for all fuel systems tested

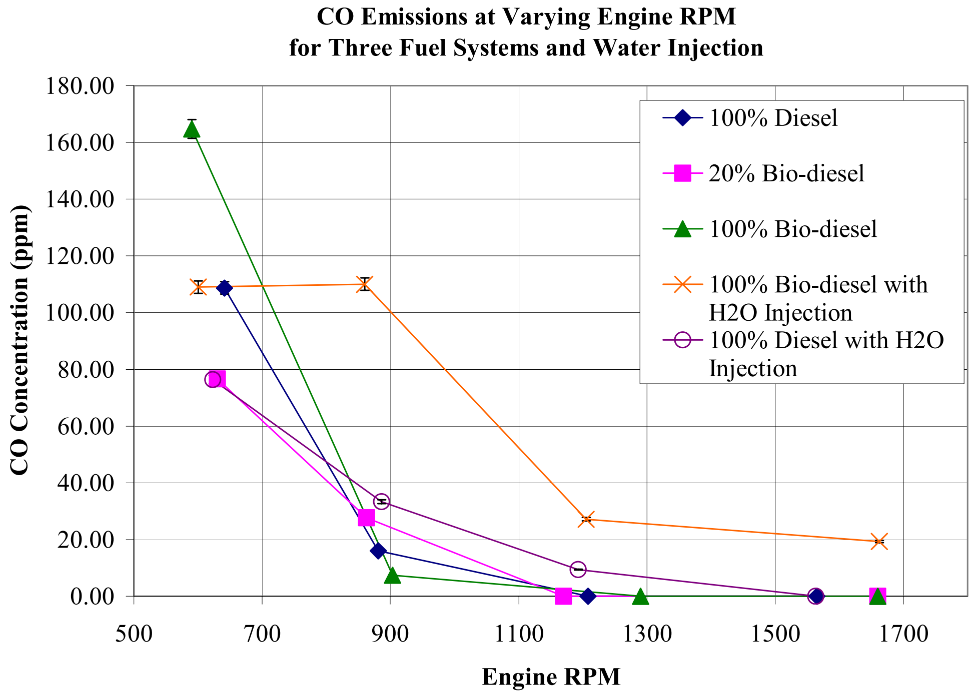


Fig. 5 CO emissions at varying engine RPM for all fuel systems tested

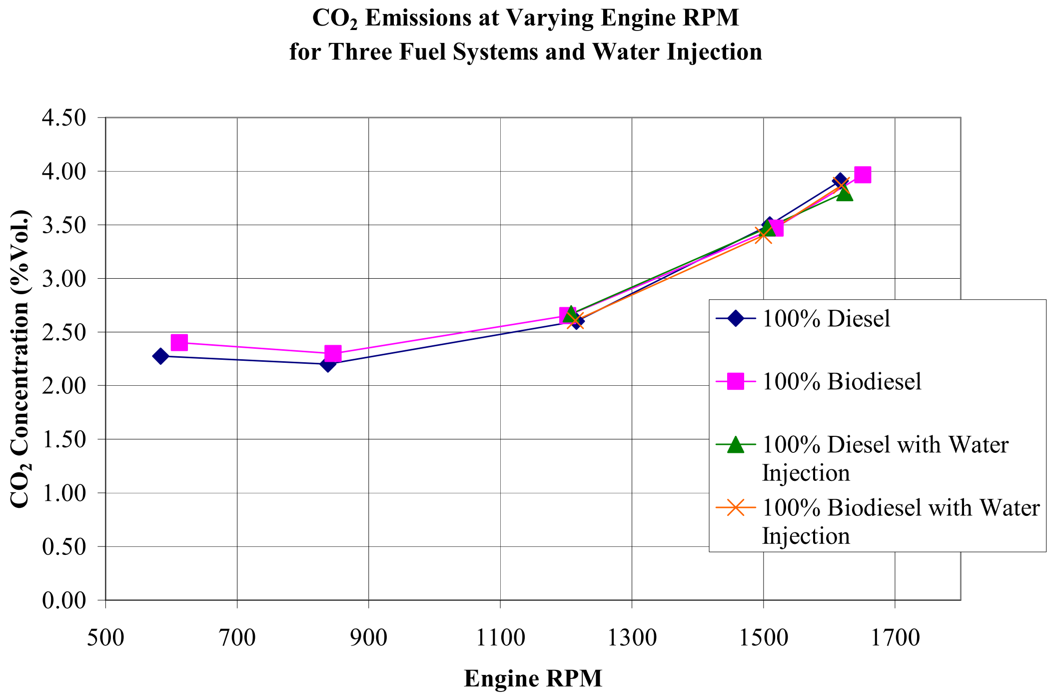


Fig. 6 CO$_2$ emissions at varying engine RPM for all fuel systems tested

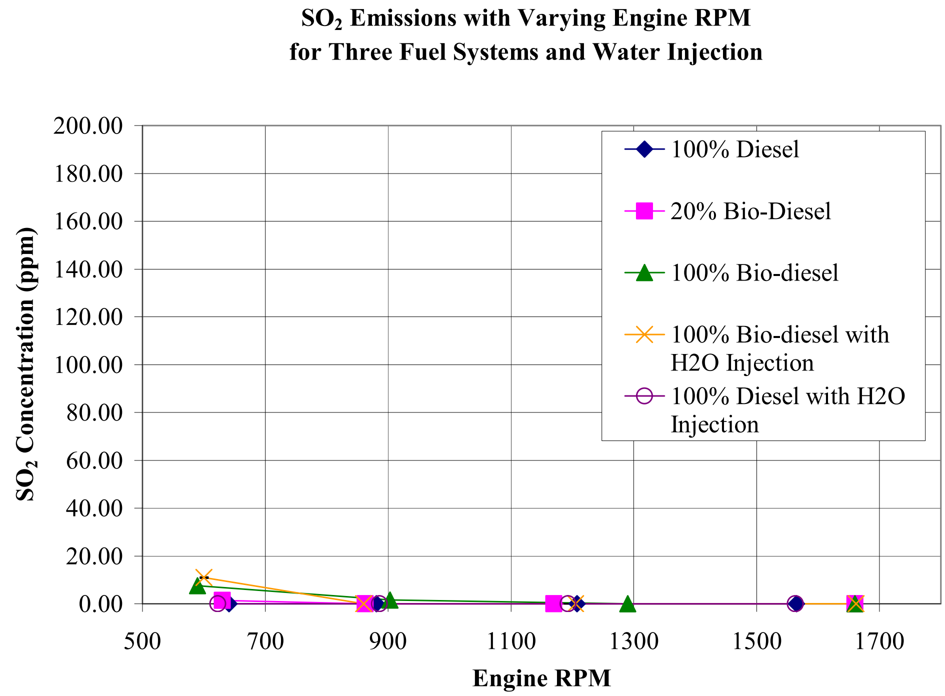


Fig. 7 SO$_2$ emissions at varying engine RPM for all fuel systems tested

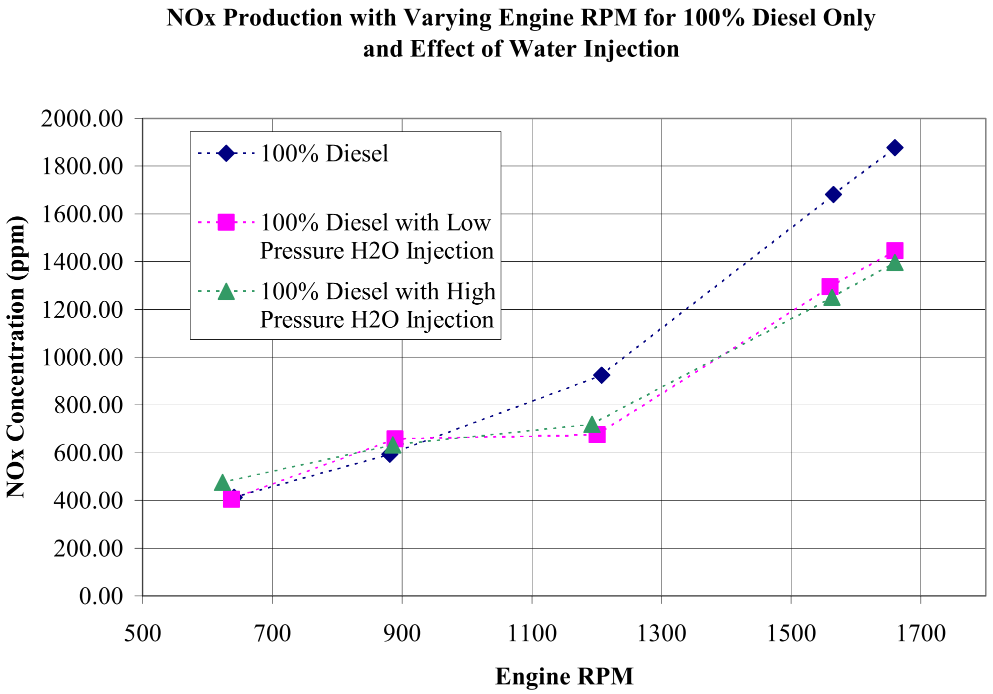


Fig. 8 Effect of water injection on NOx emissions using standard off-road diesel fuel

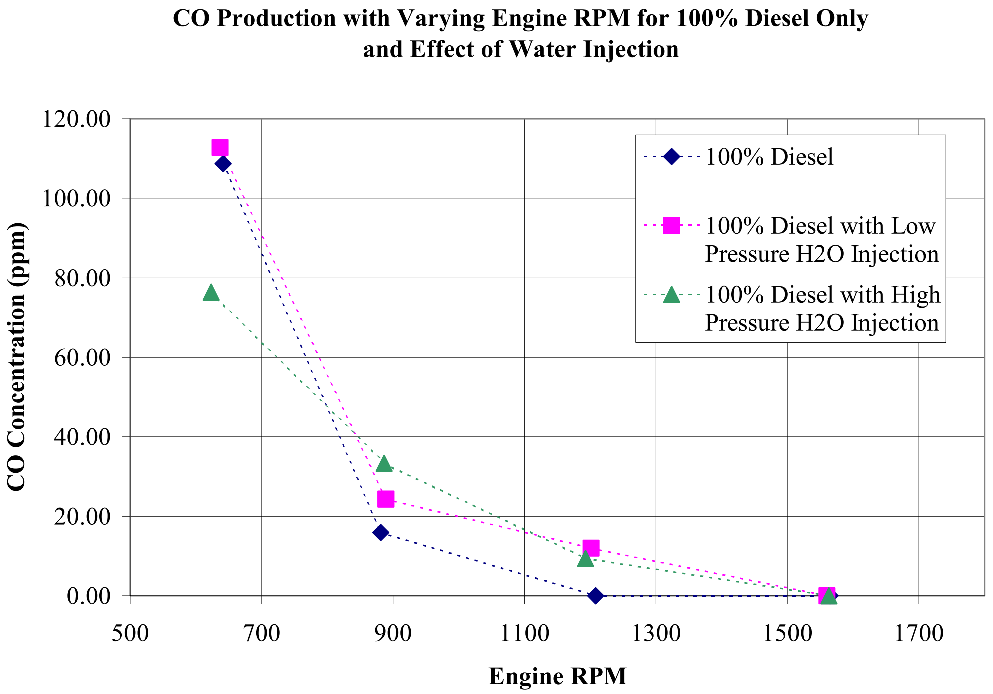


Fig. 9 Effect of water injection on CO emissions using standard off-road diesel fuel

reality presented as a function of RPM, since load and RPM cannot be varied independently (except in dynamometer testing, however these tests only simulated load and RPM conditions of tests conducted aboard the vessel). Figures 4, 5, 6, and 7 present results for NO_x, CO, CO_2 and SO_2 emissions respectively, for all fuel types tested as well as 100% bio-diesel with water injection and standard off-road diesel with water injection. Data presented for standard off-road diesel is an estimation based on dynamometer tests conducted. Emissions measurements are sensitive to load conditions, and some variation in load conditions was encountered during the baseline standard off-road diesel fuel tests, adversely affecting this data set. At this time, the original Oski engine was not available for testing on the vessel while underway. Thus the dynamometer tests were used to provide data for the baseline case. The estimated data is marked in Figure 4 by dashed lines. Figures 8 and 9 focus on NOx and CO emissions respectively from tests with and without water injection using standard off-road diesel.

All concentration results are shown with a standard error of 2% of reading. This is derived from measured instrument error of the Enerac once factory calibration has been performed. Calibration was performed on the instrument prior to all testing. The standard deviation of the time-dependent measurements was taken as an additional error for concentration measurements. However, in all cases the standard deviation of the measurements was substantially less than the instrument error of 2% of reading.

The results for NOx concentrations clearly show an increase in NOx concentration with increasing engine RPM, most likely as a result of increased cylinder temperature driving thermal NOx formation. The 100% bio-diesel case shows higher NOx formation at higher RPM than comparable standard off-road diesel cases. This is consistent with research findings that bio-diesel combustion in direct injection engines produces higher NOx levels than standard diesel fuel. The results show little difference between the 20% bio-diesel blend and the 100% bio-diesel blend. Finally the effect of the water injection system is to reduce NOx concentrations at the higher RPMs at which it is activated. The reduction in NOx using standard off-road diesel is approximately 20% at the 1200 RPM operating point, and approximately 25% at peak RPM.

An examination of the CO emissions results shows that CO concentrations decrease with increasing engine RPM for all fuel types and systems tested. This is consistent with expected behavior since at higher engine RPM cylinder temperature is increased, and there is considerable excess air in the diesel exhaust. A comparison between the 100% diesel fuel and the 20% bio-diesel blend shows very similar CO traces, with increased CO emissions in the case of the blended fuel at a middle RPM. With 100% bio-diesel fuel, the peak CO concentration at the lowest RPM tested is significantly greater than the comparable peaks for either the 100% diesel or blended fuel cases. With water injection, the peak CO concentration at lowest RPM is reduced in comparison to the 100% bio-diesel fuel without water injection. However, the effect of water injection is to spread the CO emissions over a greater RPM range, with non-zero values at all RPM settings tested. This is also true for standard off-road diesel with water injection – peak CO concentration at lowest RPM is reduced by water injection but CO production is spread over a wider RPM range.

CO_2 emissions are consistent over a wide range of RPMs for all fuels tested. CO_2 emissions are a proxy for measuring the completeness of reaction of the fuel and air, and indicate that all of the bio-diesel fuels (including 100% bio-diesel with water injection) as well as the standard off-road diesel demonstrate similar completeness of reaction. CO_2 emissions may be expected to vary between the bio-diesel test cases and the standard off-road diesel, due to the varying carbon content by mass of the two fuels. However, with the high dilution factor in a lean-burning direct injection engine, this effect is expected to be below measurability.

Finally, examination of SO_2 emissions shows that they are smaller than any other pollutant. Sulfur has as its only source impurities in the fuel. Most sulfur in the fuel is likely to be emitted directly from the exhaust duct as SO_2. Thus sulfur can be analyzed through a simple mass balance on the fuel sulfur content. Chemical assay of the bio-diesel fuel used indicates an expected sulfur content of 0.0024% by mass, and with the considerable dilution of diesel exhaust would lead to sulfur content below the measurability of this testing methodology. The standard off-road diesel used was a low sulfur variety, with similarly low sulfur content. See the appendix for an analysis of the standard off-road diesel fuel as well as the bio-diesel fuel. Any variance from the expected sulfur content is observed as direct SO_2 emissions as shown in Figure 7.

Mass Production Rate of Pollutants

Results and subsequent analysis are presented for emissions measurements on a gram per hour basis and for flow rate measurements. Pitot tube pressure measurements were averaged for all 6 points across the tube diameter to obtain an average pitot tube pressure. This pressure was then correlated to an exhaust gas velocity using calibration charts provided by Dwyer Instruments. The calibration corrected for exhaust gas temperature, barometric pressure and relative humidity. The velocity then allowed for the calculation of the mass flow rate of exhaust gas for each test, according to the formula:

$$\dot{m}_{exhaust} = \rho_{exhaust} v_{exhaust} \pi \left(D^2{}_{duct} / 4 \right)$$

where ρ is exhaust density, v is exhaust velocity and D is the duct diameter. The exhaust gas density is calculated from the known species compositions, gas temperature and pressure using an ideal gas analysis. The mass flow rate of the exhaust gas is then used to calculate the production of NO_x, CO and SO_2 species on a gram-per-hour basis according to the formula:

$$\dot{m}_{species} = C_{species} \left(\frac{MM_{species}}{MM_{exhaust}} \right) \dot{m}_{exhaust}$$

where C is the species concentration in ppm, and MM is the species and exhaust molecular mass.

In addition to mass production rates on a gram per hour basis, emissions measurement results are calculated on a gram per brake horsepower per hour basis. This is done by dividing the mass production rates by the brake horsepower, for each operating point. Brake horsepower was obtained by direct measurement from the dynamometer testing, and operating points not tested on the dynamometer were then interpolated through a least-squares fit to the curve of power versus engine RPM. Brake horsepower could also be measured through a carbon balance on the exhaust emissions to determine fuel flow rate, through the propeller curve supplied by the engine manufacturer, or through engine rack position. These alternative methods were either unavailable or prone to producing a greater error than direct measurement by the dynamometer.

Table 2. Time-averaged emissions measurements for the baseline testing, using 100% standard off-road diesel fuel

MASS PRODUCTION RATES OF GAS EMISSIONS

Test	RPM	Bhp	CO (g/hr)	CO (g/bhp-hr)	NOx (g/hr)	NOx (g/bhp-hr)	SO$_2$ (g/hr)	SO$_2$ (g/bhp-hr)
100% Diesel Baseline Tests								
1	641	23.9	175.00	7.33	713	29.9	0.00	0.00
2	881	37.4	33.00	0.88	1329	35.5	0.00	0.00
3	1208	78.6	0.00	0.00	2573	32.7	0.00	0.00
4	1565	172.5	0.00	0.00	5188	30.1	0.00	0.00
Extended	1660	208.9	0.00	0.00	5962	28.5	0.00	0.00
20/80 Bio-diesel/Diesel Blend Tests								
1	630	23.5	154.10	6.57	951	30.5	6.57	0.28
2	863	36.0	57.45	1.60	1366	37.9	0.00	0.00
3	1170	72.0	0.00	0.00	2399	33.3	0.00	0.00
4	1660	208.9	0.00	0.00	6687	32.0	0.00	0.00
100% Bio-diesel Tests								
1	590	22.1	26.38	11.80	694	31.5	27.24	1.23
2	903	39.2	16.43	0.42	1455	37.1	8.04	0.21
3	1290	94.9	0.00	0.00	3456	36.4	0.00	0.00
4	1660	208.9	0.00	0.00	7369	35.3	0.00	0.00
100% Bio-diesel with Water Injection Tests								
1	600	22.4	166.21	7.42	629	28.1	38.04	1.70
2	860	35.8	228.34	6.38	1312	36.7	0.00	0.00
3	1205	78.1	72.34	0.93	1978	25.3	0.00	0.00
4	1662	209.7	71.84	0.34	6655	31.7	0.00	0.00
100% Diesel with Low-Pressure Water Injection Tests								
1	637	23.7	182.45	7.69	704	29.7	0.00	0.00
2	889	38.0	51.06	1.34	1485	39.0	0.00	0.00
3	1201	77.3	31.53	0.41	1916	24.8	0.00	0.00
4	1560	170.7	0.00	0.00	3940	23.1	0.00	0.00
Extended	1660	208.9	0.00	0.00	4592	22.0	0.00	0.00
100% Diesel with High-Pressure Water Injection Tests								
1	623	23.2	119.68	5.16	798	34.4	0.00	0.00
2	886	37.8	70.73	1.87	1428	37.8	0.00	0.00
3	1193	75.9	24.29	0.32	1997	26.3	0.00	0.00
4	1563	171.8	0.00	0.00	3848	22.4	0.00	0.00
Extended	1660	208.9	0.00	0.00	4439	21.2	0.00	0.00

Results of the time-averaged emissions measurements for all relevant species are presented below in Table 2 for the baseline emissions testing, for the blended fuel emissions testing, for the pure bio-diesel emissions testing, for the bio-diesel fuel with water injection emissions testing, for the standard off-road diesel fuel with low-pressure water injection emissions testing, and for the standard off-road diesel fuel with high-pressure water injection emissions testing. Results in Table 2 are presented both in the format of mass production rates (g/hr) and mass production rates per brake horsepower of the engine (g/bhp-hr). These results are the average of a 5-minute measurement period for each test condition at the centerpoint of the exhaust duct.

In all test cases considered, it is observed that NOx production on a gram per hour basis is increased with increasing engine RPM under the given load conditions. This would point strongly to thermal NOx as the major NOx production mechanism, consistent with research findings on NOx production in diesel engines. It is also observed in all test cases that CO production on a gram per hour basis decreases with increasing engine RPM, potentially due to the increased engine temperature allowing for more complete combustion. With the bio-diesel fuel blends and pure bio-diesel, some SO_2 production is observed. The SO_2 production is always greatest at low RPM, since at higher rpm the percent concentration of the SO_2 in the exhaust stream drops below the lower detection threshold of the portable emissions analyzer.

A comparison between the baseline test cases and the fuel blend and pure bio-diesel test cases shows that CO emissions are generally reduced for the bio-diesel fuel test cases relative to the baseline test cases. The peak CO production rate, which occurs at lowest RPM, is higher in the baseline case (at 175 g/hr) than the blended fuel case (at approximately 154 g/hr).

An assessment of the NOx production rates on a gram per hour basis in both the bio-diesel fuel test cases and the baseline test cases shows that at low RPMs no significant difference is seen between NOx emissions in the two test cases. At mid-range RPMs and high RPMs the bio-diesel and blended cases show greater NOx production than the standard off-road diesel, becoming significantly larger at peak RPM. At high RPMs, for all fuel types, water injection has a significant impact on NOx production rates. A comparison of NOx production using standard off-road diesel with and without water injection shows that water injection reduces peak RPM NOx production by 25%. No significant difference is seen between high and low pressure water injection for the standard off-road diesel. A comparison for the bio-diesel cases with and without water injection shows a small reduction of only 9.7% with water injection. It is believed that at the time of testing the bio-diesel cases with water injection, better modulation of the water injection system could have benefited NOx emissions. Better modulation was achieved in later tests.

The comparison between the pure bio-diesel case and the bio-diesel with water injection indicates that a greater CO production is spread over a wider range of RPM. This is consistent with the reduction in peak combustion temperature caused by the water injection. However, the effect on NOx is a clear reduction in NOx production in the water injection case, versus the pure bio-diesel without water injection. This indicates that the water injection is effective at reducing cylinder temperatures sufficiently to impact NOx production.

An assessment of the CO production rates on a gram per brake horsepower per hour basis shows again that for all tests CO production rates decrease with increasing engine RPM. A similar comparison between pure diesel test cases and bio-diesel test cases can be made on a gram per brake horsepower per hour basis as for a gram per hour basis.

An assessment of the NOx production rates on a gram per brake horsepower per hour basis shows that the peak NOx production on this basis typically occurs at the midrange RPM operating point of approximately 800-900 RPM. This point combines the highest NOx production rate with lowest brake horsepower of the engine. All results show that NOx production per brake horsepower per hour decreases from the peak value with increasing engine RPM. This indicates that horsepower is increasing more rapidly than NOx production with increasing engine RPM. In all bio-diesel test cases, NOx production is greater at every operating point than pure diesel test cases on a gram per brake horsepower per hour basis, with an average increase of 11% for bio-diesel test cases than for pure diesel test cases. For pure diesel test cases, the effect of water injection is to reduce average NOx production per brake horsepower per hour by approximately 23%. For bio-diesel test cases, this average reduction is smaller at approximately 20%. Figure 10 shows NOx production rate on a gram per brake horsepower per hour basis with increasing engine RPM. Figures 11 and 12 show this same comparison for CO and SO_2 emissions.

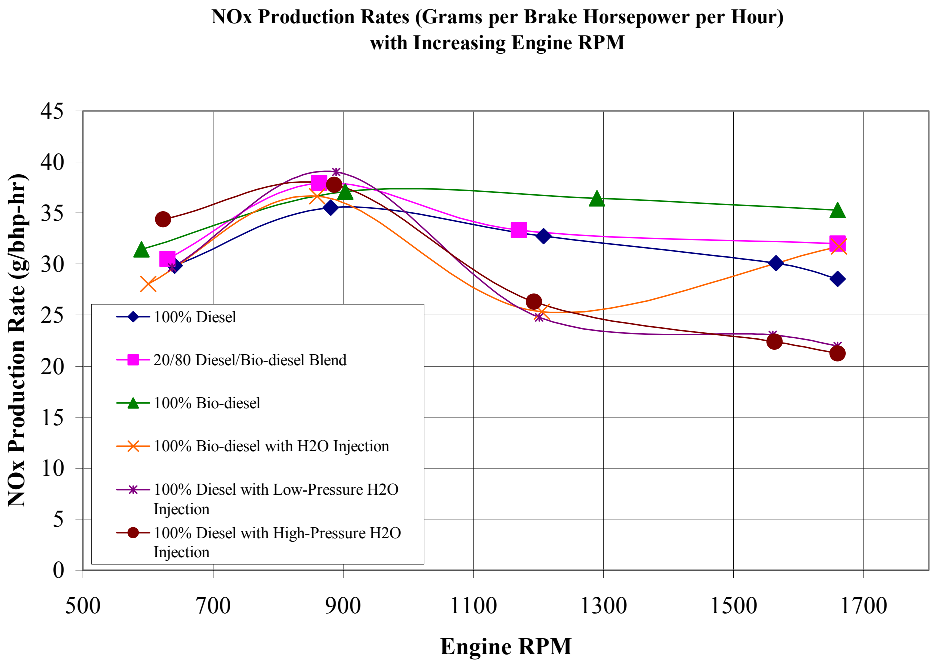


Fig. 10. NOx production rates on a gram per brake horsepower per hour basis with increasing engine RPM

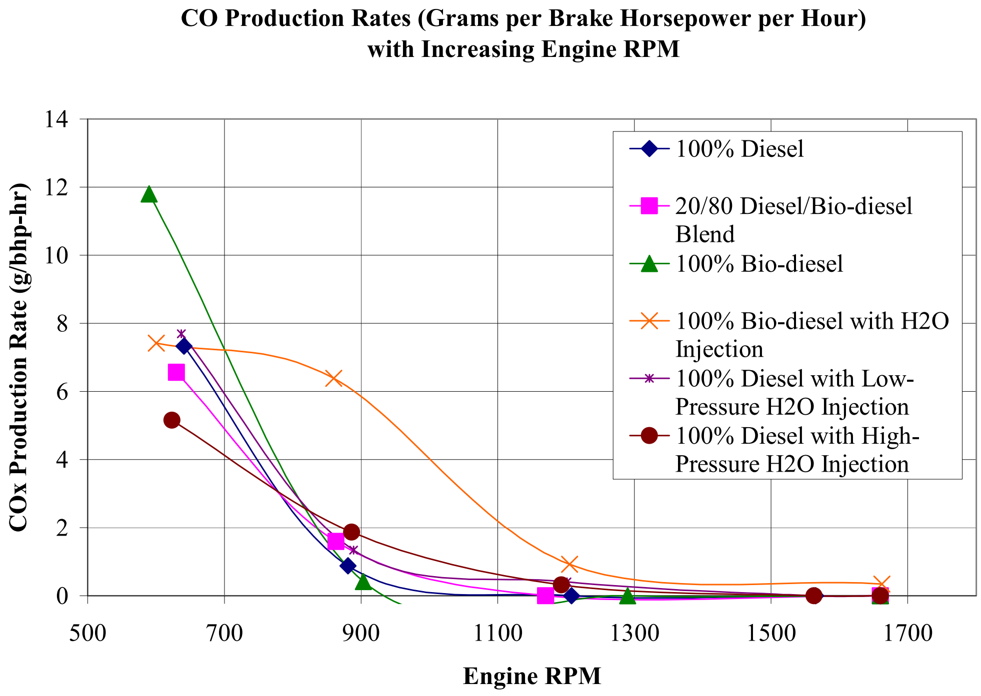


Fig. 11 CO production rates on a gram per brake horsepower per hour basis with increasing engine RPM

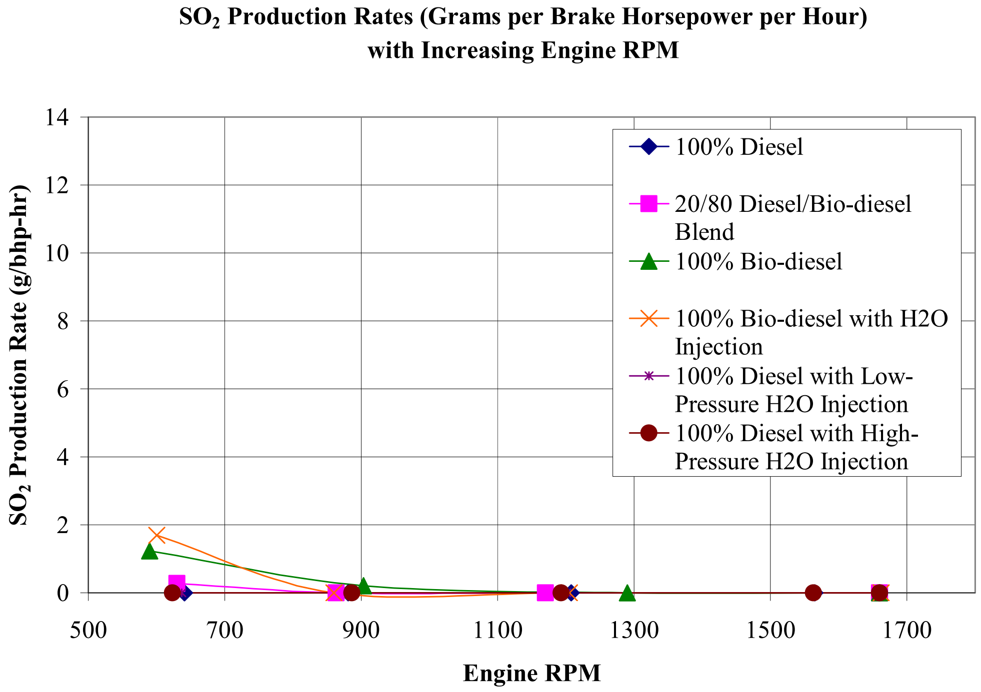


Fig. 12 SO$_2$ production rates on a gram per brake horsepower per hour basis with increasing engine RPM

Particle Measurement Results

Results are presented for particle mass production rate measurements. Tests have been conducted only with standard off road diesel, and 100% bio-diesel fuel, with and without water injection for both fuels.

In order to calculate particle mass production rates in the sample line system, the total mass of accumulated particulate matter on the filter is divided by the time of filter exposure to the exhaust stream. This sample line particle production rate is then multiplied by a scaling factor which is the ratio of the total engine exhaust mass flow rate to the sample line mass flow rate. This calculation is summarized in the following expression:

$$\dot{m}_{PM} = \left(\frac{\Delta m_{filter}}{\Delta t} \right) \frac{\dot{m}_{exhaust,total}}{\dot{m}_{sampleline}}$$

where Δm_{filter} is the mass of particulate matter accumulated on the filter, Δt is the duration of filter exposure, $\dot{m}_{exhaust,total}$ and $\dot{m}_{sampleline}$ are the exhaust and sample line mass flow rates respectively. The sample line rotameter is used to meter sample line mass flow rate, and the pitot tube exhaust gas velocity measurements are used to calculate exhaust mass flow rate, as described above. This method does not speciate the types of particulate matter accumulated on the filter, but the nature of the particulate matter is expected to be similar to that from a standard heavy-duty diesel engine – namely, solid carbon particles (soot); soluble organic fraction (SOF); sulfates due to the presence of any sulfur in the fuel; and engine oil particles. Furthermore, this method does not give an indication of particle size distribution, which would require a measurement methodology beyond the scope of this study.

Table 3 shows a summary of the results. Similarly to the gas emissions results, the data is presented on both a gram per hour basis and a gram per brake horsepower per hour basis. Results show that mass production rates of particulate matter on a gram per hour basis increase with increasing engine RPM for all test cases. This increase is driven largely by the increase in mass flow rate of exhaust with increasing engine RPM. At the highest RPM operating point, mass production rates are significantly higher than at all previous RPM operating points. This inconsistency in the data is attributed to water damage of the quartz filter, as seen in visual images of the filters shown below. However, no attempts were made to remove water from the sample prior to exposing the sample to the filter. Any drying would influence the composition of the particulate matter in the sample line, and therefore further influence the total mass of particulate matter measured on the filter. It is concluded that the particulate matter measurement methodology used here will not be effective for exhaust samples containing high water vapor content. On a gram per brake horsepower per hour basis, particulate matter production rates are seen to decrease with increasing engine RPM, with the exception of the highest RPM operating point. As noted above, the high filter weight caused by water contamination, influences the particulate matter production rate at this operating point.

Table 3. Particulate matter mass production rates on a gram per hour and gram per brake horsepower per hour basis

PARTICULATE MATTER PRODUCTION RATES			
Test	RPM	PM Production Rate (g/hr)	PM Production Rate (g/bhp-hr)
100% Diesel			
1	641	27.8	1.17
2	881	28.4	0.76
3	1208	62.9	0.80
4	1565	202.7	1.18
100% Bio-Diesel			
1	590	13.9	0.63
2	903	19.2	0.49
3	1290	29.7	0.31
4	1660	105.7	0.51
100% Diesel with Water Injection			
1	623	30.3	1.28
2	886	35.9	0.94
3	1193	56.6	0.73
4	1563	201.9	1.18
100% Bio-Diesel with Water Injection			
1	600	14.3	0.64
2	860	20.1	0.56
3	1205	48.0	0.62
4	1662	108.3	0.52

Figure 13 shows a graphical representation of the particle emissions measurement results. It can be observed in a comparison between the standard off-road diesel and the 100% bio-diesel fuels that the bio-diesel case shows significant reduction in particulate matter production rates. This is consistent with ongoing research findings that show significantly reduced particulate matter emissions from combustion of bio-diesel fuel in direct injection engines. The reduction in particulate matter mass production rates between standard off-road diesel and 100% bio-diesel is approximately 54% as an average of all operating points. A similar reduction of approximately 60% is seen in a comparison between the standard off-road diesel and 100% bio-diesel cases with water injection. The overall effect of water injection is to raise the particulate mass production rate slightly. This is an indication that the lower cylinder temperatures expected with water injection may increase the unburned hydrocarbon loading, which may subsequently serve as a precursor in soot formation.

Figure 14 shows digital images of the quartz filters after exposure to the exhaust stream. As can be seen, the lowest RPM for each of the two testing configurations displays the darkest filter. This is a strong indication that at this RPM, particle concentrations in the exhaust stream are highest.

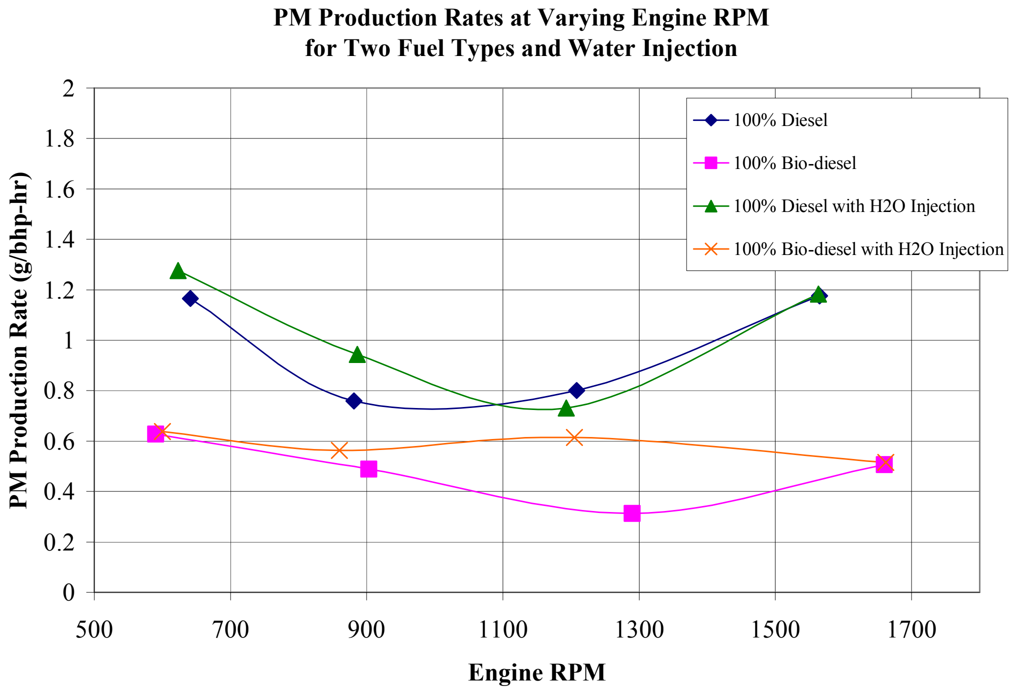


Fig. 13. Particulate matter production rates on a gram per brake horsepower per hour basis at varying engine RPM for two fuel types and water injection

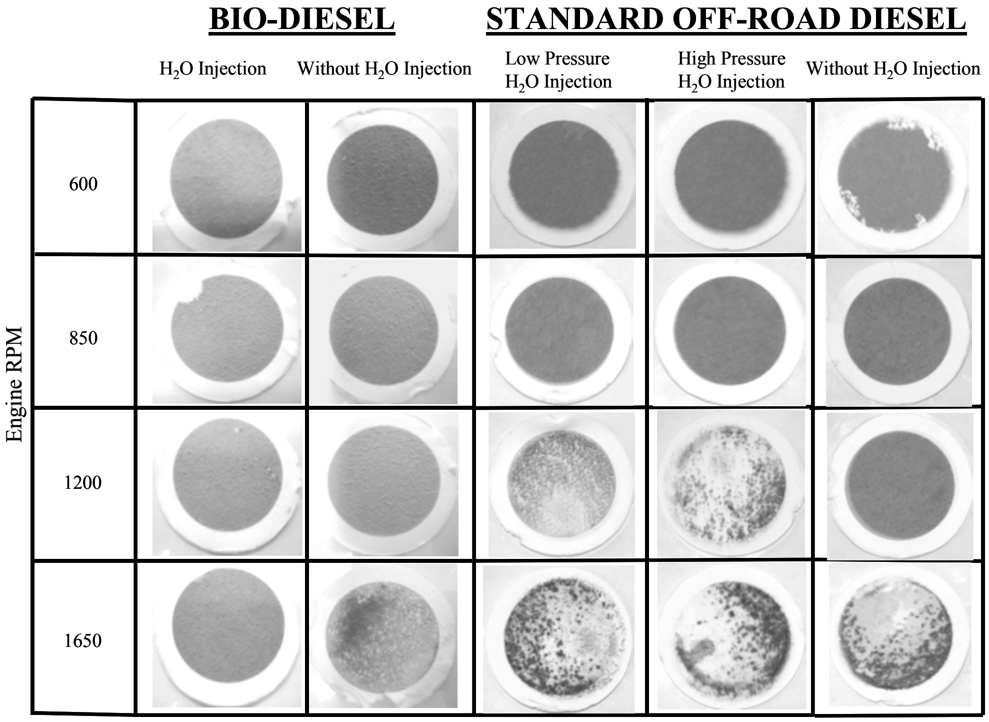


Fig. 14 Digital images of quartz particulate filters after exposure to exhaust stream

IV Conclusions

A testing methodology has been proposed and demonstrated for determining emissions from a marine diesel engine aboard the Blue & Gold Fleet vessel Oski. Tests were conducted to determine emissions of NOx, CO, SO_2, and particulate matter on a concentration and mass production basis. The effects of varying the fuel from the standard off-road diesel fuel to a processed vegetable-based bio-diesel fuel, and of the addition of a water injection system with both fuel types, are explored.

Results show that the effect on emissions of switching to a bio-diesel fuel is to increase NOx production, particularly at peak engine RPM. This result is shown in both the concentration format data and the mass production rate data. The bio-diesel fuel displays improved peak CO emissions over the standard off-road diesel fuel, but spreads CO emissions over a wider RPM range than the standard off-road diesel. However, for both fuels the overall CO production is small compared to NOx production levels. The most pronounced effect on emissions of bio-diesel combustion is the reduction in particulate matter production. Particle mass production rates with bio-diesel fuel are only 50 – 60% of those measured with standard off-road diesel fuel.

A water injection system has been tested with all fuel types. The effect of the water injection is to reduce NOx emissions at engine operating conditions of 1200 RPMs or higher, at which point the water injection system is activated. The reduction in NOx at these high RPM operating conditions varies from approximately 10% to 25%. Higher percent reductions are seen with standard off-road diesel fuel than with the bio-diesel fuel. No significant adverse effect is seen on the CO production or particulate matter production with the water injection system. The reductions in NOx production from the water injection system are significant, and could potentially be substantially increased by a better control scheme for the water injection. Further testing would be required to determine optimal operating conditions for the water injection system. It should be noted that hydrocarbon measurements – expected to be insignificant for diesel engines using both fuel systems tested – become more significant as water injection is increased. Any future testing of an optimized water injection system would require a hydrocarbon emissions measurement system. This may also apply to colder after-cooler circuits in the future.

The results presented here show the impact of both the fuel system and water injection system on emissions from a marine diesel source. These results are intended for use in determining the impact of these modifications on emissions, and to aid in planning for emissions reduction in future engine systems.

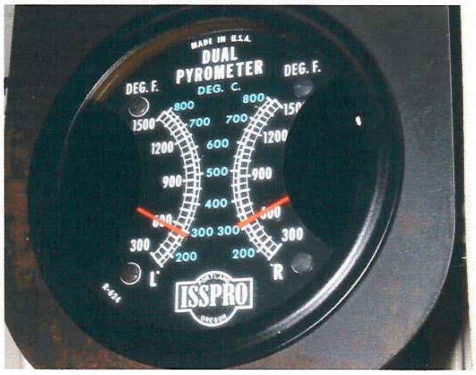
V. Appendices

Appendix A

The figures below are images from testing conducted aboard the Blue & Gold Fleet vessel Oski, showing the instrumentation used as well as images of the setup in the exhaust duct.

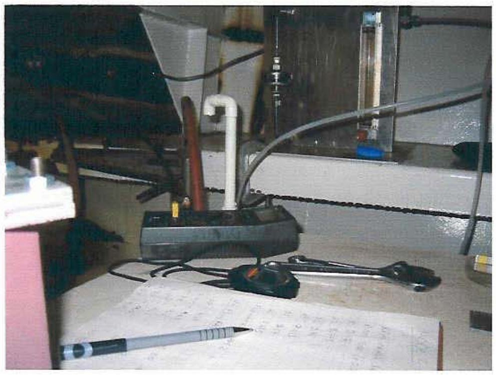
Oski's Detroit 12V71N

Tachometer



Pyrometers

Digital Tachometer

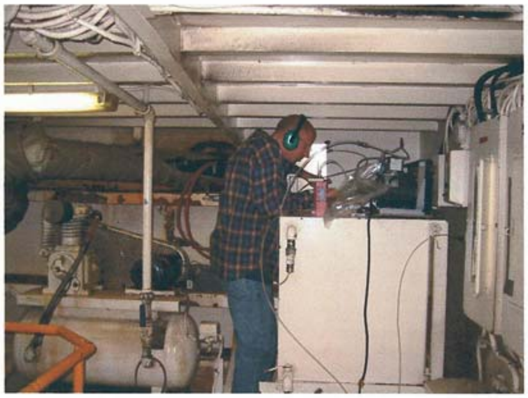


Digital Pyrometer

Sample Port with probes

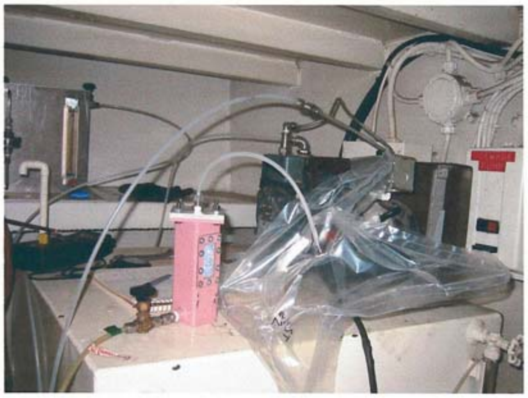
Test Equipment and Logger

Particulate Trap and Filter/Dryer

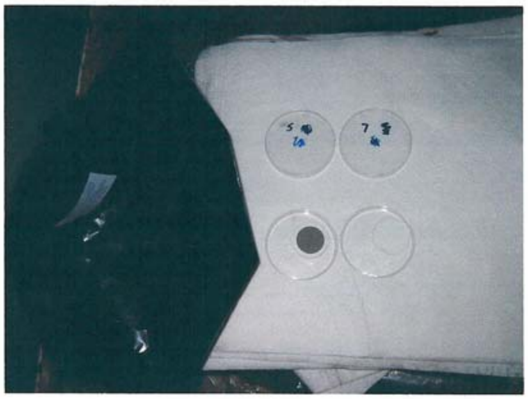


Engineer Amnon in a tight place

Engineer w/ Stopwatch collecting samples

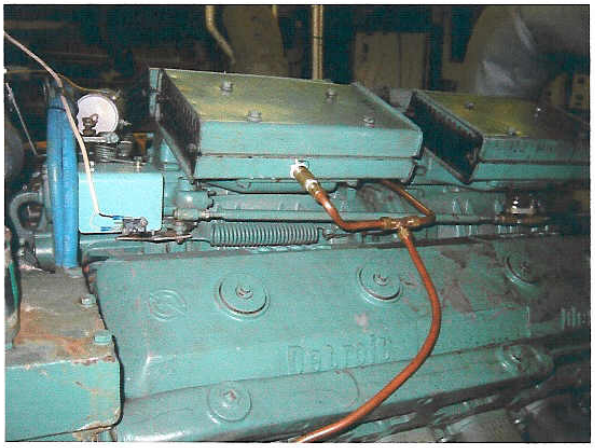


Filling Hydrocarbon test bag for lab test

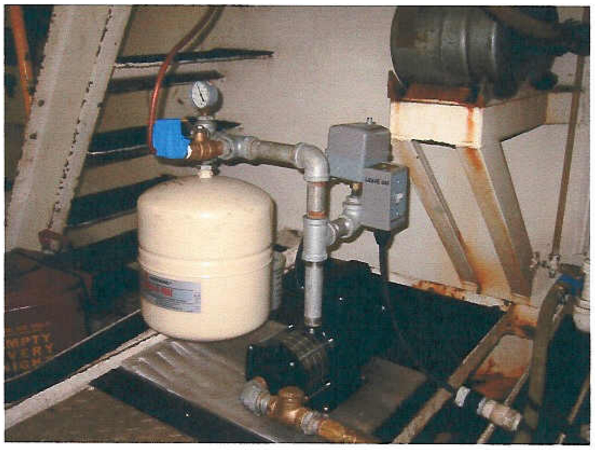


Particulate samples, new and collected

Water Injection Controls



Water spray nozzles in intake



Water supply conditioner

Appendix B

Copy of fuel analysis conducted on the standard off-road diesel fuel used in this testing

G.P. Resources, Inc. Fuel Specifications
Marketing and Supply May 25, 2000
Technical Support and Development

LOW SULFUR EPA DIESEL (RED)

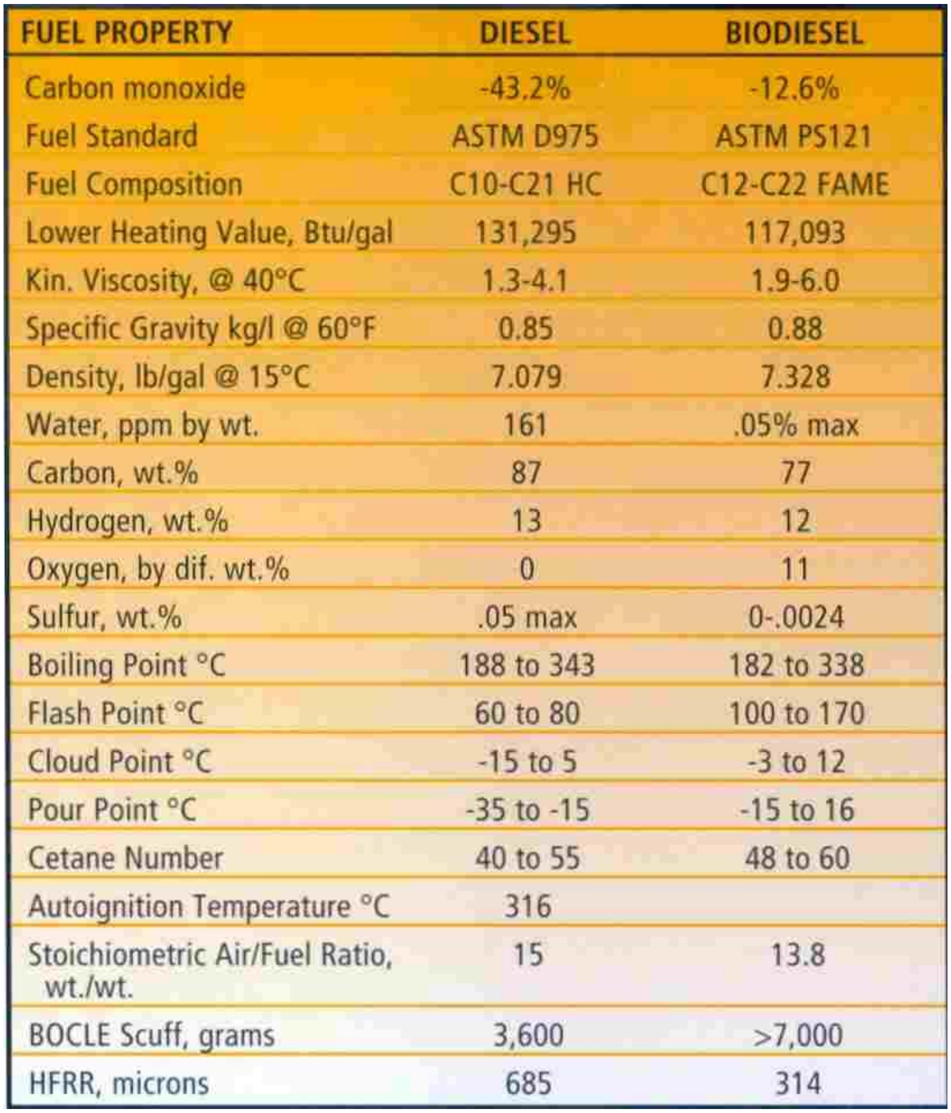
BASIC SPECIFICATIONS

SPECIFICATIONS/UNITS	METHOD ASTM	(RANGES) LIMITS MIN	MAX	TYPICAL
COMBUSTION				
Cetane No.	D613	40	(45)	42
Gravity, deg. API	D1298	30	(35)	33
Specific Gravity	D1298		0.8762	0.86
Ash, wt %	D482		0.01	0.001
VOLITILITY				
Distillation, deg F	D86			
90% recovery			650	603
End Point				629
FLUIDITY				
Cloud Point, deg F	500, 2386 (1)		5	0
Winter (Nov-Mar)				
Pour Point	D97			
Summer (Apr-Oct)			10	0
Winter (Nov-Mar)			-20	-25
Viscosity @ 104F, cSt	D445	1.9	4.2	3.9
CLEANLINESS & PURITY				
Water & Sediment, wt %	D1796		0.05	Trace
Color			4.0	1.5
CORROSIVENESS				
Total Sulfur, wt %	D129, D1552		0.05	0.04
SAFETY				
Flash Point, deg F	D93, D3828	140		170
ADDITIVES				
Red Dye B, ppm	(Supplied by G P)	25		25

Attachment A

Appendix C

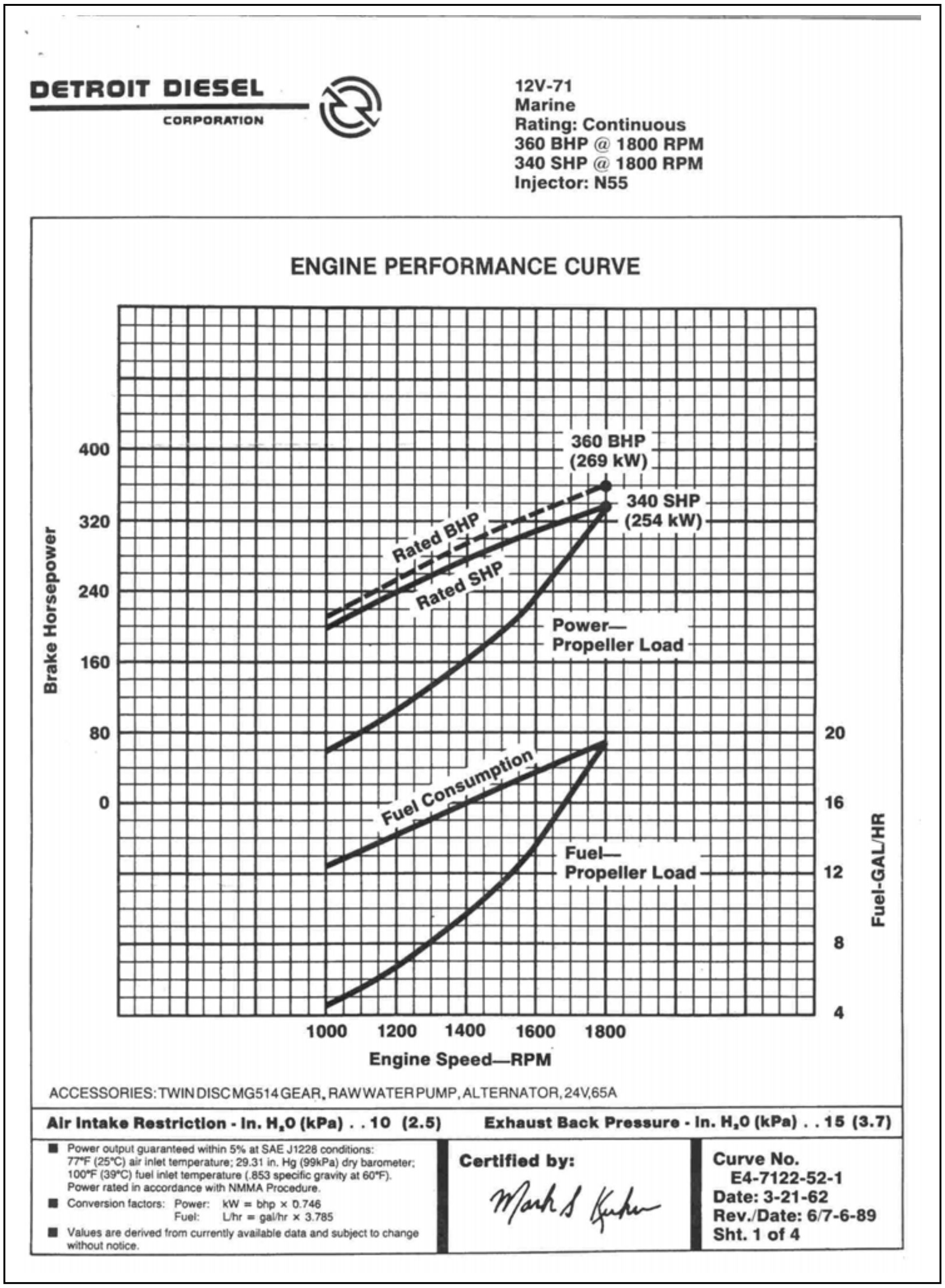
Chemical assay and specifications for bio-diesel fuel used. Reproduced from report published for the U.S. Department of Energy (DOE) by the National Renewable Energy Laboratory, DOE/GO-102001-1449, revised September 2001.



FUEL PROPERTY	DIESEL	BIODIESEL
Carbon monoxide	-43.2%	-12.6%
Fuel Standard	ASTM D975	ASTM PS121
Fuel Composition	C10-C21 HC	C12-C22 FAME
Lower Heating Value, Btu/gal	131,295	117,093
Kin. Viscosity, @ 40°C	1.3-4.1	1.9-6.0
Specific Gravity kg/l @ 60°F	0.85	0.88
Density, lb/gal @ 15°C	7.079	7.328
Water, ppm by wt.	161	.05% max
Carbon, wt.%	87	77
Hydrogen, wt.%	13	12
Oxygen, by dif. wt.%	0	11
Sulfur, wt.%	.05 max	0-.0024
Boiling Point °C	188 to 343	182 to 338
Flash Point °C	60 to 80	100 to 170
Cloud Point °C	-15 to 5	-3 to 12
Pour Point °C	-35 to -15	-15 to 16
Cetane Number	40 to 55	48 to 60
Autoignition Temperature °C	316	
Stoichiometric Air/Fuel Ratio, wt./wt.	15	13.8
BOCLE Scuff, grams	3,600	>7,000
HFRR, microns	685	314

Appendix D

Engine performance curve for Detroit Diesel 12V-71 marine engine, reproduced from Detroit Diesel Corp. publication.



DETROIT DIESEL
CORPORATION

12V-71
Marine
Rating: Continuous
360 BHP @ 1800 RPM
340 SHP @ 1800 RPM
Injector: N55

ENGINE PERFORMANCE CURVE

ACCESSORIES: TWIN DISC MG514 GEAR, RAW WATER PUMP, ALTERNATOR, 24V,65A

Air Intake Restriction - In. H_2O (kPa) . . 10 (2.5) **Exhaust Back Pressure - In. H_2O (kPa) . . 15 (3.7)**

- Power output guaranteed within 5% at SAE J1228 conditions: 77°F (25°C) air inlet temperature; 29.31 in. Hg (99kPa) dry barometer; 100°F (39°C) fuel inlet temperature (.853 specific gravity at 60°F). Power rated in accordance with NMMA Procedure.
- Conversion factors: Power: kW = bhp × 0.746
  Fuel: L/hr = gal/hr × 3.785
- Values are derived from currently available data and subject to change without notice.

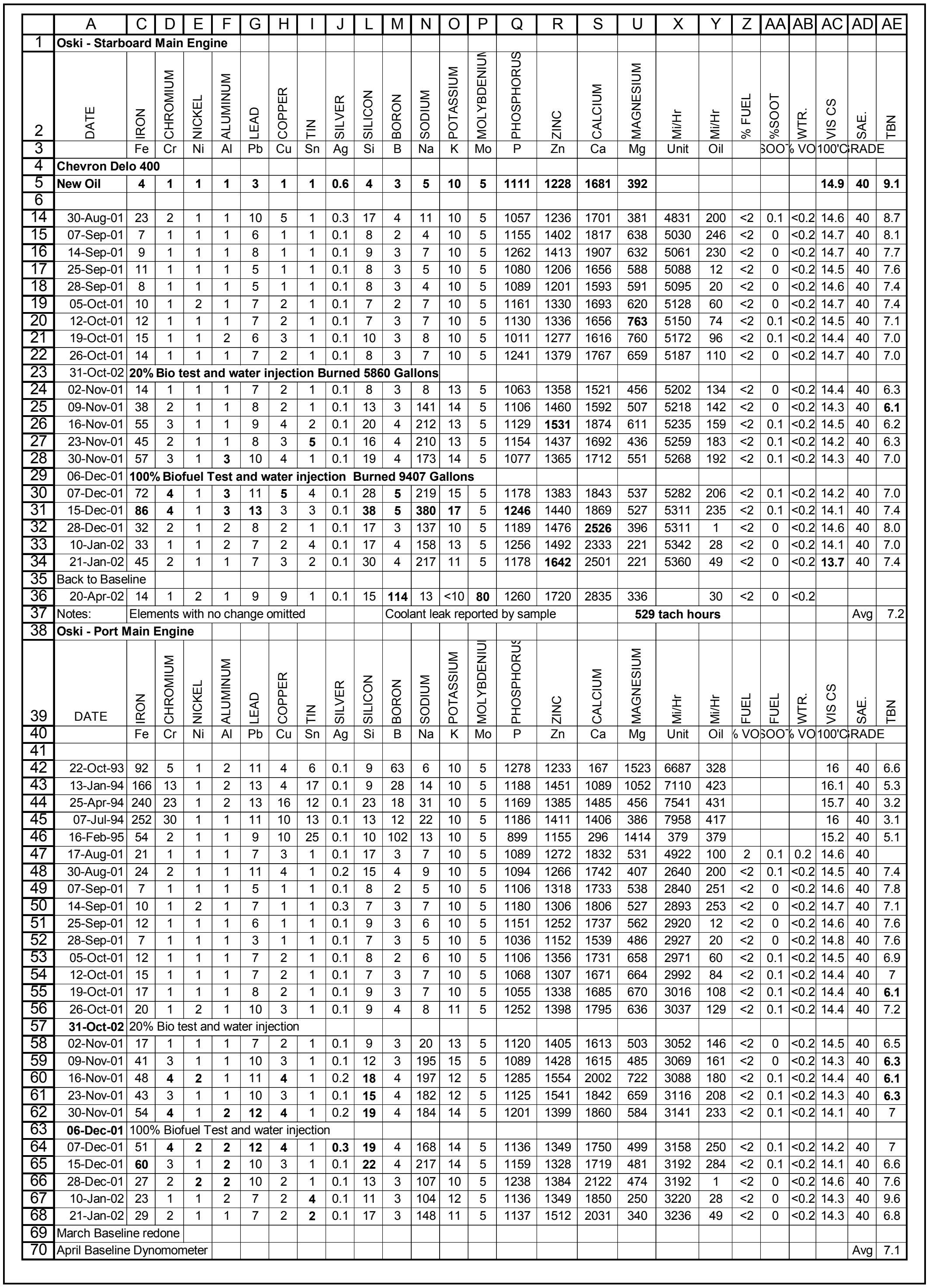
Certified by:

Mark S [illegible]

Curve No.
E4-7122-52-1
Date: 3-21-62
Rev./Date: 6/7-6-89
Sht. 1 of 4

Appendix E

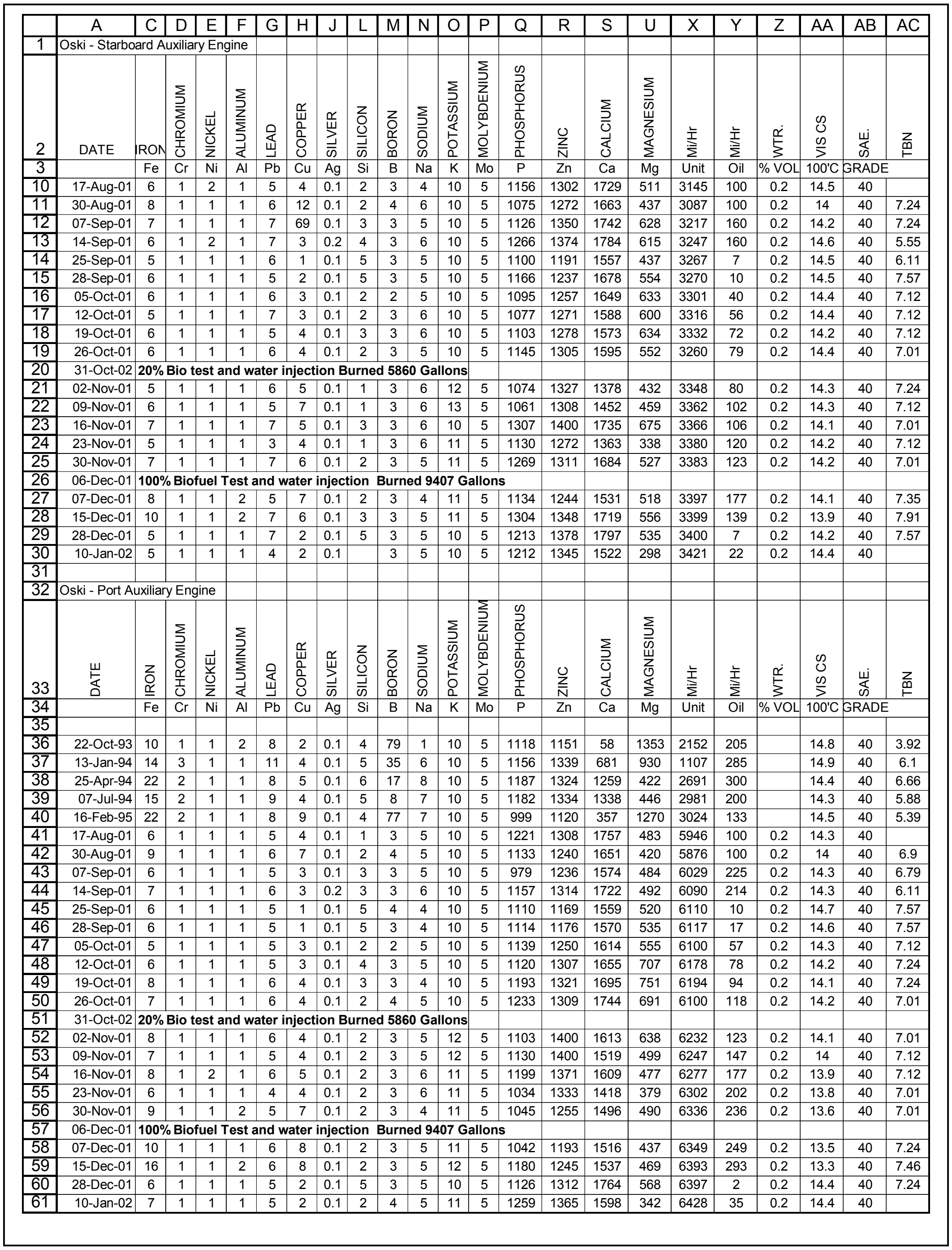
A lube oil analysis performed on the main engines after engine testing was completed is included.



	A	C	D	E	F	G	H	I	J	L	M	N	O	P	Q	R	S	U	X	Y	Z	AA	AB	AC	AD	AE
1	**Oski - Starboard Main Engine**																									
2	DATE	IRON	CHROMIUM	NICKEL	ALUMINUM	LEAD	COPPER	TIN	SILVER	SILICON	BORON	SODIUM	POTASSIUM	MOLYBDENIUM	PHOSPHORUS	ZINC	CALCIUM	MAGNESIUM	Mi/Hr	Mi/Hr	% FUEL	%SOOT	WTR.	VIS CS	SAE.	TBN
3		Fe	Cr	Ni	Al	Pb	Cu	Sn	Ag	Si	B	Na	K	Mo	P	Zn	Ca	Mg	Unit	Oil		SOOT	% VO	100'C	GRADE	
4	**Chevron Delo 400**																									
5	**New Oil**	**4**	**1**	**1**	**1**	**3**	**1**	**1**	**0.6**	**4**	**3**	**5**	**10**	**5**	**1111**	**1228**	**1681**	**392**						**14.9**	**40**	**9.1**
6																										
14	30-Aug-01	23	2	1	1	10	5	1	0.3	17	4	11	10	5	1057	1236	1701	381	4831	200	<2	0.1	<0.2	14.6	40	8.7
15	07-Sep-01	7	1	1	1	6	1	1	0.1	8	2	4	10	5	1155	1402	1817	638	5030	246	<2	0	<0.2	14.7	40	8.1
16	14-Sep-01	9	1	1	1	8	1	1	0.1	9	3	7	10	5	1262	1413	1907	632	5061	230	<2	0	<0.2	14.7	40	7.7
17	25-Sep-01	11	1	1	1	5	1	1	0.1	8	3	5	10	5	1080	1206	1656	588	5088	12	<2	0	<0.2	14.5	40	7.6
18	28-Sep-01	8	1	1	1	5	1	1	0.1	8	3	4	10	5	1089	1201	1593	591	5095	20	<2	0	<0.2	14.6	40	7.4
19	05-Oct-01	10	1	2	1	7	2	1	0.1	7	2	7	10	5	1161	1330	1693	620	5128	60	<2	0	<0.2	14.7	40	7.4
20	12-Oct-01	12	1	1	1	7	2	1	0.1	7	3	7	10	5	1130	1336	1656	**763**	5150	74	<2	0.1	<0.2	14.5	40	7.1
21	19-Oct-01	15	1	1	2	6	3	1	0.1	10	3	8	10	5	1011	1277	1616	760	5172	96	<2	0.1	<0.2	14.4	40	7.0
22	26-Oct-01	14	1	1	1	7	2	1	0.1	8	3	7	10	5	1241	1379	1767	659	5187	110	<2	0	<0.2	14.7	40	7.0
23	31-Oct-02	**20% Bio test and water injection Burned 5860 Gallons**																								
24	02-Nov-01	14	1	1	1	7	2	1	0.1	8	3	8	13	5	1063	1358	1521	456	5202	134	<2	0	<0.2	14.4	40	6.3
25	09-Nov-01	38	2	1	1	8	2	1	0.1	13	3	141	14	5	1106	1460	1592	507	5218	142	<2	0	<0.2	14.3	40	**6.1**
26	16-Nov-01	55	3	1	1	9	4	2	0.1	20	4	212	13	5	1129	**1531**	1874	611	5235	159	<2	0.1	<0.2	14.5	40	6.2
27	23-Nov-01	45	2	1	1	8	3	**5**	0.1	16	4	210	13	5	1154	1437	1692	436	5259	183	<2	0.1	<0.2	14.2	40	6.3
28	30-Nov-01	57	3	1	**3**	10	4	1	0.1	19	4	173	14	5	1077	1365	1712	551	5268	192	<2	0.1	<0.2	14.3	40	7.0
29	06-Dec-01	**100% Biofuel Test and water injection Burned 9407 Gallons**																								
30	07-Dec-01	72	**4**	1	**3**	11	**5**	4	0.1	28	**5**	219	15	5	1178	1383	1843	537	5282	206	<2	0.1	<0.2	14.2	40	7.0
31	15-Dec-01	**86**	**4**	1	**3**	**13**	3	3	0.1	**38**	**5**	**380**	**17**	5	**1246**	1440	1869	527	5311	235	<2	0.1	<0.2	14.1	40	7.4
32	28-Dec-01	32	2	1	2	8	2	1	0.1	17	3	137	10	5	1189	1476	**2526**	396	5311	1	<2	0	<0.2	14.6	40	8.0
33	10-Jan-02	33	1	1	2	7	2	4	0.1	17	4	158	13	5	1256	1492	2333	221	5342	28	<2	0	<0.2	14.1	40	7.0
34	21-Jan-02	45	2	1	1	7	3	2	0.1	30	4	217	11	5	1178	**1642**	2501	221	5360	49	<2	0	<0.2	**13.7**	40	7.4
35	Back to Baseline																									
36	20-Apr-02	14	1	2	1	9	9	1	0.1	15	**114**	13	<10	**80**	1260	1720	2835	336		30	<2	0	<0.2			
37	Notes:	Elements with no change omitted									Coolant leak reported by sample							**529 tach hours**							Avg	7.2
38	**Oski - Port Main Engine**																									
39	DATE	IRON	CHROMIUM	NICKEL	ALUMINUM	LEAD	COPPER	TIN	SILVER	SILICON	BORON	SODIUM	POTASSIUM	MOLYBDENIUM	PHOSPHORUS	ZINC	CALCIUM	MAGNESIUM	Mi/Hr	Mi/Hr	FUEL	FUEL	WTR.	VIS CS	SAE.	TBN
40		Fe	Cr	Ni	Al	Pb	Cu	Sn	Ag	Si	B	Na	K	Mo	P	Zn	Ca	Mg	Unit	Oil	% VO	SOOT	% VO	100'C	GRADE	
41																										
42	22-Oct-93	92	5	1	2	11	4	6	0.1	9	63	6	10	5	1278	1233	167	1523	6687	328				16	40	6.6
43	13-Jan-94	166	13	1	2	13	4	17	0.1	9	28	14	10	5	1188	1451	1089	1052	7110	423				16.1	40	5.3
44	25-Apr-94	240	23	1	2	13	16	12	0.1	23	18	31	10	5	1169	1385	1485	456	7541	431				15.7	40	3.2
45	07-Jul-94	252	30	1	1	11	10	13	0.1	13	12	22	10	5	1186	1411	1406	386	7958	417				16	40	3.1
46	16-Feb-95	54	2	1	1	9	10	25	0.1	10	102	13	10	5	899	1155	296	1414	379	379				15.2	40	5.1
47	17-Aug-01	21	1	1	1	7	3	1	0.1	17	3	7	10	5	1089	1272	1832	531	4922	100	2	0.1	0.2	14.6	40	
48	30-Aug-01	24	2	1	1	11	4	1	0.2	15	4	9	10	5	1094	1266	1742	407	2640	200	<2	0.1	<0.2	14.5	40	7.4
49	07-Sep-01	7	1	1	1	5	1	1	0.1	8	2	5	10	5	1106	1318	1733	538	2840	251	<2	0	<0.2	14.6	40	7.8
50	14-Sep-01	10	1	2	1	7	1	1	0.3	7	3	7	10	5	1180	1306	1806	527	2893	253	<2	0	<0.2	14.7	40	7.1
51	25-Sep-01	12	1	1	1	6	1	1	0.1	9	3	6	10	5	1151	1252	1737	562	2920	12	<2	0	<0.2	14.6	40	7.6
52	28-Sep-01	7	1	1	1	3	1	1	0.1	7	3	5	10	5	1036	1152	1539	486	2927	20	<2	0	<0.2	14.8	40	7.6
53	05-Oct-01	12	1	1	1	7	2	1	0.1	8	2	6	10	5	1106	1356	1731	658	2971	60	<2	0.1	<0.2	14.5	40	6.9
54	12-Oct-01	15	1	1	1	7	2	1	0.1	7	3	7	10	5	1068	1307	1671	664	2992	84	<2	0.1	<0.2	14.4	40	7
55	19-Oct-01	17	1	1	1	8	2	1	0.1	9	3	7	10	5	1055	1338	1685	670	3016	108	<2	0.1	<0.2	14.4	40	**6.1**
56	26-Oct-01	20	1	2	1	10	3	1	0.1	9	4	8	11	5	1252	1398	1795	636	3037	129	<2	0.1	<0.2	14.4	40	7.2
57	**31-Oct-02**	20% Bio test and water injection																								
58	02-Nov-01	17	1	1	1	7	2	1	0.1	9	3	20	13	5	1120	1405	1613	503	3052	146	<2	0	<0.2	14.5	40	6.5
59	09-Nov-01	41	3	1	1	10	3	1	0.1	12	3	195	15	5	1089	1428	1615	485	3069	161	<2	0	<0.2	14.3	40	**6.3**
60	16-Nov-01	48	**4**	**2**	1	11	**4**	1	0.2	**18**	4	197	12	5	1285	1554	2002	722	3088	180	<2	0.1	<0.2	14.4	40	**6.1**
61	23-Nov-01	43	3	1	1	10	3	1	0.1	**15**	4	182	12	5	1125	1541	1842	659	3116	208	<2	0.1	<0.2	14.3	40	**6.3**
62	30-Nov-01	54	**4**	1	**2**	**12**	**4**	1	0.2	**19**	4	184	14	5	1201	1399	1860	584	3141	233	<2	0.1	<0.2	14.1	40	7
63	**06-Dec-01**	100% Biofuel Test and water injection																								
64	07-Dec-01	51	**4**	**2**	**2**	**12**	**4**	1	**0.3**	**19**	4	168	14	5	1136	1349	1750	499	3158	250	<2	0.1	<0.2	14.2	40	7
65	15-Dec-01	**60**	3	1	**2**	10	3	1	0.1	**22**	4	217	14	5	1159	1328	1719	481	3192	284	<2	0.1	<0.2	14.1	40	6.6
66	28-Dec-01	27	2	**2**	**2**	10	2	1	0.1	13	3	107	10	5	1238	1384	2122	474	3192	1	<2	0	<0.2	14.6	40	7.6
67	10-Jan-02	23	1	1	2	7	2	**4**	0.1	11	3	104	12	5	1136	1349	1850	250	3220	28	<2	0	<0.2	14.3	40	9.6
68	21-Jan-02	29	2	1	1	7	2	**2**	0.1	17	3	148	11	5	1137	1512	2031	340	3236	49	<2	0	<0.2	14.3	40	6.8
69	March Baseline redone																									
70	April Baseline Dynomometer																								Avg	7.1

Appendix F

A lube oil analysis performed on the auxiliary engines after engine testing was completed is included.



	A	C	D	E	F	G	H	J	L	M	N	O	P	Q	R	S	U	X	Y	Z	AA	AB	AC
1	Oski - Starboard Auxiliary Engine																						
2	DATE	IRON	CHROMIUM	NICKEL	ALUMINUM	LEAD	COPPER	SILVER	SILICON	BORON	SODIUM	POTASSIUM	MOLYBDENUM	PHOSPHORUS	ZINC	CALCIUM	MAGNESIUM	Mi/Hr	Mi/Hr	WTR.	VIS CS	SAE.	TBN
3		Fe	Cr	Ni	Al	Pb	Cu	Ag	Si	B	Na	K	Mo	P	Zn	Ca	Mg	Unit	Oil	% VOL	100'C	GRADE	
10	17-Aug-01	6	1	2	1	5	4	0.1	2	3	4	10	5	1156	1302	1729	511	3145	100	0.2	14.5	40	
11	30-Aug-01	8	1	1	1	6	12	0.1	2	4	6	10	5	1075	1272	1663	437	3087	100	0.2	14	40	7.24
12	07-Sep-01	7	1	1	1	7	69	0.1	3	3	5	10	5	1126	1350	1742	628	3217	160	0.2	14.2	40	7.24
13	14-Sep-01	6	1	2	1	7	3	0.2	4	3	6	10	5	1266	1374	1784	615	3247	160	0.2	14.6	40	5.55
14	25-Sep-01	5	1	1	1	6	1	0.1	5	3	5	10	5	1100	1191	1557	437	3267	7	0.2	14.5	40	6.11
15	28-Sep-01	6	1	1	1	5	2	0.1	5	3	5	10	5	1166	1237	1678	554	3270	10	0.2	14.5	40	7.57
16	05-Oct-01	6	1	1	1	6	3	0.1	2	2	5	10	5	1095	1257	1649	633	3301	40	0.2	14.4	40	7.12
17	12-Oct-01	5	1	1	1	7	3	0.1	2	3	6	10	5	1077	1271	1588	600	3316	56	0.2	14.4	40	7.12
18	19-Oct-01	6	1	1	1	5	4	0.1	3	3	6	10	5	1103	1278	1573	634	3332	72	0.2	14.2	40	7.12
19	26-Oct-01	6	1	1	1	6	4	0.1	2	3	5	10	5	1145	1305	1595	552	3260	79	0.2	14.4	40	7.01
20	31-Oct-02	**20% Bio test and water injection Burned 5860 Gallons**																					
21	02-Nov-01	5	1	1	1	6	5	0.1	1	3	6	12	5	1074	1327	1378	432	3348	80	0.2	14.3	40	7.24
22	09-Nov-01	6	1	1	1	5	7	0.1	1	3	6	13	5	1061	1308	1452	459	3362	102	0.2	14.3	40	7.12
23	16-Nov-01	7	1	1	1	7	5	0.1	3	3	6	10	5	1307	1400	1735	675	3366	106	0.2	14.1	40	7.01
24	23-Nov-01	5	1	1	1	3	4	0.1	1	3	6	11	5	1130	1272	1363	338	3380	120	0.2	14.2	40	7.12
25	30-Nov-01	7	1	1	1	7	6	0.1	2	3	5	11	5	1269	1311	1684	527	3383	123	0.2	14.2	40	7.01
26	06-Dec-01	**100% Biofuel Test and water injection Burned 9407 Gallons**																					
27	07-Dec-01	8	1	1	2	5	7	0.1	2	3	4	11	5	1134	1244	1531	518	3397	177	0.2	14.1	40	7.35
28	15-Dec-01	10	1	1	2	7	6	0.1	3	3	5	11	5	1304	1348	1719	556	3399	139	0.2	13.9	40	7.91
29	28-Dec-01	5	1	1	1	7	2	0.1	5	3	5	10	5	1213	1378	1797	535	3400	7	0.2	14.2	40	7.57
30	10-Jan-02	5	1	1	1	4	2	0.1		3	5	10	5	1212	1345	1522	298	3421	22	0.2	14.4	40	
31																							
32	Oski - Port Auxiliary Engine																						
33	DATE	IRON	CHROMIUM	NICKEL	ALUMINUM	LEAD	COPPER	SILVER	SILICON	BORON	SODIUM	POTASSIUM	MOLYBDENIUM	PHOSPHORUS	ZINC	CALCIUM	MAGNESIUM	Mi/Hr	Mi/Hr	WTR.	VIS CS	SAE.	TBN
34		Fe	Cr	Ni	Al	Pb	Cu	Ag	Si	B	Na	K	Mo	P	Zn	Ca	Mg	Unit	Oil	% VOL	100'C	GRADE	
35																							
36	22-Oct-93	10	1	1	2	8	2	0.1	4	79	1	10	5	1118	1151	58	1353	2152	205		14.8	40	3.92
37	13-Jan-94	14	3	1	1	11	4	0.1	5	35	6	10	5	1156	1339	681	930	1107	285		14.9	40	6.1
38	25-Apr-94	22	2	1	1	8	5	0.1	6	17	8	10	5	1187	1324	1259	422	2691	300		14.4	40	6.66
39	07-Jul-94	15	2	1	1	9	4	0.1	5	8	7	10	5	1182	1334	1338	446	2981	200		14.3	40	5.88
40	16-Feb-95	22	2	1	1	8	9	0.1	4	77	7	10	5	999	1120	357	1270	3024	133		14.5	40	5.39
41	17-Aug-01	6	1	1	1	5	4	0.1	1	3	5	10	5	1221	1308	1757	483	5946	100	0.2	14.3	40	
42	30-Aug-01	9	1	1	1	6	7	0.1	2	4	5	10	5	1133	1240	1651	420	5876	100	0.2	14	40	6.9
43	07-Sep-01	6	1	1	1	5	3	0.1	3	3	5	10	5	979	1236	1574	484	6029	225	0.2	14.3	40	6.79
44	14-Sep-01	7	1	1	1	6	3	0.2	3	3	6	10	5	1157	1314	1722	492	6090	214	0.2	14.3	40	6.11
45	25-Sep-01	6	1	1	1	5	1	0.1	5	4	4	10	5	1110	1169	1559	520	6110	10	0.2	14.7	40	7.57
46	28-Sep-01	6	1	1	1	5	1	0.1	5	3	4	10	5	1114	1176	1570	535	6117	17	0.2	14.6	40	7.57
47	05-Oct-01	5	1	1	1	5	3	0.1	2	2	5	10	5	1139	1250	1614	555	6100	57	0.2	14.3	40	7.12
48	12-Oct-01	6	1	1	1	5	3	0.1	4	3	5	10	5	1120	1307	1655	707	6178	78	0.2	14.2	40	7.24
49	19-Oct-01	8	1	1	1	6	4	0.1	3	3	4	10	5	1193	1321	1695	751	6194	94	0.2	14.1	40	7.24
50	26-Oct-01	7	1	1	1	6	4	0.1	2	4	5	10	5	1233	1309	1744	691	6100	118	0.2	14.2	40	7.01
51	31-Oct-02	**20% Bio test and water injection Burned 5860 Gallons**																					
52	02-Nov-01	8	1	1	1	6	4	0.1	2	3	5	12	5	1103	1400	1613	638	6232	123	0.2	14.1	40	7.01
53	09-Nov-01	7	1	1	1	5	4	0.1	2	3	5	12	5	1130	1400	1519	499	6247	147	0.2	14	40	7.12
54	16-Nov-01	8	1	2	1	6	5	0.1	2	3	6	11	5	1199	1371	1609	477	6277	177	0.2	13.9	40	7.12
55	23-Nov-01	6	1	1	1	4	4	0.1	2	3	6	11	5	1034	1333	1418	379	6302	202	0.2	13.8	40	7.01
56	30-Nov-01	9	1	1	2	5	7	0.1	2	3	4	11	5	1045	1255	1496	490	6336	236	0.2	13.6	40	7.01
57	06-Dec-01	**100% Biofuel Test and water injection Burned 9407 Gallons**																					
58	07-Dec-01	10	1	1	1	6	8	0.1	2	3	5	11	5	1042	1193	1516	437	6349	249	0.2	13.5	40	7.24
59	15-Dec-01	16	1	1	2	6	8	0.1	2	3	5	12	5	1180	1245	1537	469	6393	293	0.2	13.3	40	7.46
60	28-Dec-01	6	1	1	1	5	2	0.1	5	3	5	10	5	1126	1312	1764	568	6397	2	0.2	14.4	40	7.24
61	10-Jan-02	7	1	1	1	5	2	0.1	2	4	5	11	5	1259	1365	1598	342	6428	35	0.2	14.4	40	