Alternative Fuel For Marine Application

FINAL REPORT

29 February 2012

PREPARED BY: U.S Maritime Administration (MARAD)

PREPARED FOR: Naval Fuels & Lubes CFT

Alternative Fuel For Marine Application
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Date:
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14. ABSTRACT
As part of an ongoing MARAD alternative fuels test initiative, shipboard tests were conducted using an algal fuel that the U.S. Navy is currently evaluating. Details about the test planning and preparation, performance and emissions testing, and test results are provided. Testing was performed on the T/S STATE OF MICHIGAN which is a training ship operated by the Great Lakes Maritime Academy and owned by MARAD.

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Executive Summary

The U.S. Maritime Administration (MARAD) is participating in the U.S. Navy's ongoing efforts to test alternative fuels for marine use by demonstrating their applicability on commercial vessels. In support of this effort, the Navy provided neat hydrotreated renewable diesel (HRD), derived from the hydroprocessing of algal oils, for operational and exhaust emission testing onboard the T/S STATE OF MICHIGAN. The T/S STATE OF MICHIGAN is owned by MARAD and operated by the Great Lakes Maritime Academy in Traverse City, Michigan. It is a retired Stalwart Class Modified Tactical General Ocean Surveillance Ship (T-AGOS 1) built by Tacoma Boat. The vessel was commissioned in August 1985 as PERSISTENT (T-AGOS 6) and was struck and transferred to Great Lakes Maritime Academy (GLMA) in 2002 and renamed the T/S STATE OF MICHIGAN. The vessel is an electric drive vessel with four propulsion diesel generators and two propulsion motors. In 2009-2010 the control system was upgraded and the tankage was modified.

This test was performed in conjunction with the component testing, full-scale testing, and demonstration projects being conducted by the Navy using a hydrotreated renewable diesel fuel. A combination of underway and pier-side testing was accomplished over a three month period: September through November 2011. The test fuel was a 50/50 blend by volume of HRD fuel provided by the Navy, and Ultra Low Sulfur Diesel (ULSD) purchased by MARAD. This report discusses the details of the equipment, vessel, and operational and emission tests that were conducted to evaluate the performance of the test fuel against neat ULSD on the same engine. Performance and emissions data were collected both underway and pier-side.

The vessel has diesel-electric propulsion with four caterpillar D-398 compression ignition engines; one of these diesel generator engines was selected as the test engine. The diesel generators set power for both of the propulsion motors propelling the ship and provide the electrical power for the hotel loads. The ULSD was blended with the neat HRD fuel in a 50/50-by-volume in the field at a local fuel company. The 50/50 blend fuel was then loaded on the ship and kept isolated by the tankage of the ship. ULSD from the same batch of fuel was also loaded and used for the baseline ULSD emission tests and to run the other shipboard generator sets for the duration of the test.

The Number 4 Ship Service Diesel Generator (SSDG) was used for the baseline and blend fuel exhaust emission testing and also for the remainder of the testing. Modifications were made to the exhaust stack to accommodate the exhaust emissions test equipment. The Number 4 SSDG was tested for over 440 hours with over 9,500 gallons of the 50/50 blend fuel. Some minor modifications were required to the engine to permit insertion of test instrumentation; however, the equipment was restored to original condition upon completion of the test.

Exhaust emission testing was performed while underway on Lake Michigan using the baseline ULSD assessed on day one and then the 50/50 blend fuel on the second day. The same profile was run using both fuels. Emission testing was conducted using the ISO 8178 (D2) test cycle and was performed by University of California –Riverside (UCR) for a period of two days at the start of the test. The same diesel generator engine was used for both fuels.

The 50/50 blend test fuel produced lower measured emissions of NO_x, CO, CO_2, and Particulate Matter (PM) compared to the neat ULSD. ISO 8178 calls for the measurement of exhaust emissions at five test points, then, using the defined weighting factors, a weighted emission factor is created. The weighted emissions of NO_x, CO, and CO_2 were 10, 18, and 5 percent lower for the 50/50 blend test fuel than for the same engine operated on the ULSD,

respectively. The switch in fuel also resulted in a 25 percent reduction in the weighted emissions of $PM_{2.5}$.

When emission testing was completed, a series of underway and pier-side test runs were conducted to observe the plant operation and accumulate data for the remaining engine hours. After all testing, the engine internal conditions were assessed again using a combination of visual inspection and physical testing. At the conclusion of the testing period, an engine inspection was performed and compared to the initial pre-test engine inspection. Both inspections were performed by the same Caterpillar Service Representative to ensure consistent evaluation of the material condition of the components. The service representative concluded that the effects of the biofuel on the engine were the same as those of #2 ultra low sulfur diesels. The remainder of the test fuel will be used to conduct a long-term stability test. The U.S. Coast Guard developed a test plan to isolate the remainder of the two test fuels, the ULSD baseline fuel and the 50/50 blend fuel, into two similar tanks for the winter months. Each designated storage tank was drained of fuel, inspected, and filled with a test fuel. Samples were drawn for analysis. Microbiological testing was performed and samples were sent to the Navy's Naval Air Systems Command Laboratory in Maryland for analysis. The results of the long-term test program are expected in April 2012.

MARAD has concluded as a result of this testing that the 50/50 blend test fuel, as blended for this test, appears to be an acceptable drop-in replacement fuel for the ULSD used on the T/S STATE OF MICHIGAN as well as other commercial vessels having a similar power plant. The testing successfully demonstrated all facets of drop-in fuel performance, from fuel husbandry (loading, transferring, and supply to the engine), to superior exhaust emission performance. Addition of the HRD to the ULSD also provided an improvement in heating value which resulted in slightly better fuel consumption performance.

Acknowledgements

The authors express their gratitude to the Great Lakes Maritime Academy Staff and crew members for their support throughout this test program. Through their efforts as well as the efforts of University of California – Riverside, Crystal Flash Energy, and Michigan Caterpillar, we were able to successfully complete this project in the short timeframe required. We especially thank Chief Sobolewski for his outstanding efforts and tenacity. Without him and his shipboard engineering staff doing the heavy lifting of on-site engineering support for this project, it would not have been possible. We would also like to acknowledge several other Government Agencies for their support and participation including U.S Navy, EPA, NOAA, and Army Corps of Engineers. We are grateful to the U.S. Naval Air Systems personnel (Sherry Williams, Andy McDaniel, and Emily Lim) for their donation of the fuel, fuel testing, and technical advice and their support throughout this project. Finally, we also appreciate the support of the U.S. Coast Guard to provide some additional benefit to our study with the ongoing long-term fuel stability assessment project.

List of Acronyms

ABS	American Bureau of Shipping
ASTM	American Society for Testing and Materials
CFT	Cross Functional Team
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DoD	U.S. Department of Defense
DT	dilution tunnel
EC	elemental carbon
ECE	Economic Commission for Europe
EDG	emergency diesel generator
EF	Emission factors
EMF	electromagnetic frequency
EP	exhaust pipe
EPA	Environmental Protection Agency
ETV	Environmental Technology Verification
FAME	Fatty Acid Methyl Ester
FFP	fit for purpose
GLMA	Great Lakes Maritime Academy
HRD	hydrotreated renewable diesel
HRD76	hydrotreated renewable F76
IMO	International Maritime Organization
ISO	International Organization for Standardization
MARAD	Maritime Administration
MCR	maximum continuous rating
NOAA	National Oceanographic and Atmospheric Administration
NO_x	oxide of nitrogen
OC	organic carbon
OPEC	Organization of Arab Petroleum Exporting Countries
PM	particulate matter
$PM_{2.5}$	particulate matter with a mean aerodynamic diameter less than 2.5 microns
SO_x	oxide of sulfur
SP	sampling probe
SSDG	ship service diesel generators
STBD	starboard
TC	total carbon
TT	transfer tube
ULSD	ultra-low sulfur diesel
UCR	University of California – Riverside
VN	venturi

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Foreword

The following report has been reviewed for clarity and technical accuracy. The report satisfactorily addresses the agreement between the U.S. Navy and the U.S Maritime Administration for support of the Navy's Alternative Fuel Test Program. The methods used are consistent with standard testing programs.

Sujit Ghosh
Project Engineer
U.S. Maritime Administration

1. Introduction

As part of its mission, the Maritime Administration (MARAD) seeks to provide technical support that benefits the commercial maritime industry. At the beginning of 2011, MARAD began an initiative to complement Department of Defense (DoD) activity relating to the use of alternative fuels by demonstrating their applicability on commercial vessels. Of specific interest was the U.S. Navy program evaluating the use of drop-in alternative fuels to the traditional F-76 and JP-5 fuels used on its ships. Test planning began in late July 2011, preparation and testing commenced on the T/S STATE OF MICHIGAN in early September, and concluded in late November.

This report documents the project execution and results. It is organized in sections that provide an overview of the project including the background, planning, preparation, execution, and results. Appendices are also provided with more extensive details and data as well as the complete exhaust emissions test report prepared by the University of California – Riverside (UCR).

2. Background

Over the past forty years, there have been periods where the supply of petroleum-derived fuels has been problematic. Energy planners continue to predict a point at which "peak oil" production will be reached and petroleum reserves and production will begin to dwindle. Geopolitical issues have influenced the supply of petroleum as well. For example, in 1973, the members of the Organization of Arab Petroleum Exporting Countries (OPEC) declared an embargo of oil. The ensuing disruption demonstrated the fragility of the world and U.S. energy economy.

The embargo affected all sectors of the energy economy, but the impact to the transportation sector, which uses a significant portion of the liquid fuel consumed, was particularly strong. At that time, the U.S. Government established the Department of Energy, in part to reduce the Nation's reliance on foreign oil. Significant research and testing was done to develop national non-traditional petroleum sources such as shale oil and tar sands. Research also started to focus on producing synthetic fuel from coal sources using the Fischer Tropsch process employed by the Germans during World War II and used extensively in South Africa today. Today, supply and pricing issues continue to challenge the transportation sector.

The past decade has seen another pressure on the petroleum supply: the remarkable growth in petroleum demand by highly populated nations like India and China. This is causing additional strain on the world petroleum supply and price. In response, there has been a resurgence of interest in finding an alternative to petroleum fuel in the transportation sector. While synthetic fuel is an option that continues to be discussed, researched, and developed, costs and environmental issues associated with global climate change have limited worldwide acceptance of many of these technologies. New alternative fuels and particularly "renewable" fuels have emerged over the past decade and are beginning to establish a foothold in the energy landscape. These renewable fuels get their name from the fact that the feed stock is grown, harvested, and processed into a fuel capable of being combusted. An example of this is the use of ethanol made from corn and other grain crops which is added to gasoline, resulting in the reduction in the amount of gasoline in each gallon of automobile fuel. The term "biofuel" is used to describe the fuels created using a renewable feedstock source. More recently "drop-in" fuels have emerged. Drop-in fuel refers to any fuel that can be used in place of its petroleum counterpart without requiring any modifications to the fuel tank, fuel system, or engine components.

As these fuels are being developed to replace the current gasoline, diesel, and kerosene fuels used in the transportation sector, whose use has had its own challenges. For instance, all of the byproduct and performance characteristics of standard petroleum-derived fuels are well understood. The same is not true of the new biofuels because they were being derived from other feedstocks and produced by different processes. Further, tests of previous generations of biofuels have resulted in unexpected consequences: engine failure, fuel leakage, filter clogs, etc. Today, significant work is underway in the renewable fuel sector to research and develop feedstocks, establish specification parameters, and ensure that these renewable fuels will work effectively as an alternative to petroleum fuel.

As with other parts of the transportation sector, the maritime component has been working to understand these new renewable fuels in an effort to ensure that they can be used successfully in the ship and marine environment should they become economically viable. Engine manufacturers, owners and operators, and the marine engineering community have been experimenting, evaluating, and testing various biofuels for several years. This report discusses the tests performed by MARAD on a commercial ship using HRD fuel that the Navy is currently evaluating for use within its fleet of ships.

2.1 Historical

Over 100 years ago, the standard fuel for world naval powers was coal. In early 1910, several countries began transitioning their fleet logistic plans to a new alternative fuel: petroleum. In 1911, the first Navy destroyer, DD 22 USS PAULDING, was designed for use as a petroleum-fueled steam-powered ship. At the time, no infrastructure was in place to support petroleum fueling.

Throughout the next 100 years, both naval and maritime communities completed the transition from coal to petroleum-based fuels. During this transition, another major evolution occurred: marine fleets began to eliminate the complex and less efficient steam-drive propulsion plants in favor of simpler and more efficient gas turbine and diesel-powered propulsion plants. This transition was made possible by the use of petroleum fuel.

In 1980, the Marine Transportation Research Board published a report on alternative fuels for maritime use[1]. The study concluded that the commercial maritime industry is totally dependent on petroleum-derived fuels. The Board also concluded that the maritime industry depends on other industries for development of technology that produces new alternative fuels as well as for prime mover technologies that can use these newer fuels.

At the time of this study, a significant number of steam-powered ships were still in the active commercial fleet. While the study looked forward 20 years, to 2000, only fuels like synfuels (derived from tar sand, shale, and coal liquid), coal, nuclear, and sail were ranked as having a higher probability of future application. Fuels such as methanol, ethanol, and methane were ranked as having a lower probability for successful implementation. The key recommendation in the 1980 study is that "Coal is the primary alternative marine fuel; every effort should be made to implement its use:"

The Report was based on the knowledge of the alternative fuels and shipboard power plants of the time. Today there are a wider variety of alternative fuels including hydrogen, natural gas, and biofuels, in use or being developed. There is also a new class of power plants: using fuel cells. Currently, the simplest alternative fuel for use in marine applications appears to be "drop-in" fuels that perform the same basic function as petroleum without requiring modification to the ship's fuel handling, power plant, or exhaust handling systems while producing lower hazardous emissions.

2.2 Navy Alternative Fuel Program

In 2009, Secretary of the Navy established a goal of increasing the Navy and Marine Corps use of alternative energy to 50 percent by 2020. As part of this initiative, the Secretary also announced a goal to demonstrate a green carrier strike group operating on 50-percent biofuels by 2012 and to sail that green carrier strike group by 2016. All DoD tactical fuel is purchased from competitive sources subject to several military specifications. These specifications were developed based upon the properties of petroleum-derived fuels. As new non-petroleum sources of fuel are developed, they must be fully tested to ensure that they perform similarly to or better than petroleum fuels in the Navy's various propulsion systems.

[1] "Alternative Fuels for Maritime Use", Maritime Transportation Research Board, National Research Council, 1980.

To address these concerns, the Navy developed a fuel specification plan, which was developed with input on current petroleum properties, discussions with power plant manufacturers, and internal discussions with the Navy.

Figure 1 shows the fuel qualification process developed by the Navy. Included in the program are fit for purpose (FFP) property tests.

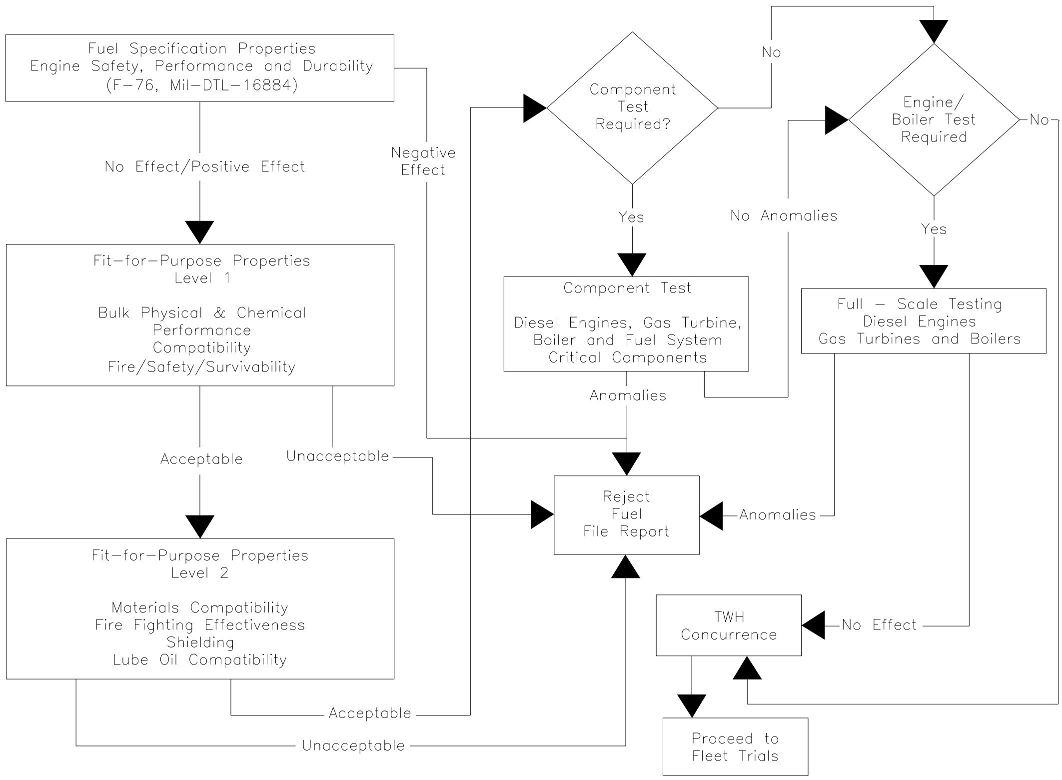


Figure 1. Navy Test Program Protocol

The FFP tests comprise parameters important to the Navy, but not included in the specification because they always fall in the acceptable range with regard to petroleum, component, and full-scale testing as well as platform and field testing. These tests include compatibility with current Navy fuels and fuel logistics, material compatibility, firefighting, long-term storage requirements, etc. The goal of this process is to ensure that any new fuel used as a drop-in replacement will not require existing infrastructure or propulsion hardware to be modified.

The first class of fuels being qualified for ship propulsion is HRD. HRD derived from algal oils is being used as the representative feedstock to qualify this class of fuels. This fuel was produced to a Navy specification and was specifically designed and processed to be blended 50/50 by volume with NATO F-76 fuel, which is the military diesel fuel typically used by the Navy for ship propulsion. This 50/50 blend of HRD with F-76 has already successfully completed specification and most FFP and component testing. It is currently undergoing full-scale engine testing and platform demonstrations.

The final step in the qualification process is to complete platform and field testing. The Navy has begun testing on several craft and ship platforms. To further its knowledge on the fuel's performance and its potential viability for commercial application, the Navy partnered with MARAD.

2.3 MARAD Maritime Alternative Fuel Initiative

As part of the U.S. Department of Transportation, MARAD performs ongoing activities related to alternative fuels, exhaust emissions, and carbon footprint reduction with respect to the commercial maritime fleet. Included in these efforts are initiatives for evaluating the use of natural gas, hydrogen, and other alternative fuels on commercial ships. In addition, MARAD has been actively participating in work related to "drop-in" fuels such as biofuels and biodiesel, B5, B20, B50, and B100. Through agreement with the Navy and as part of its alternative fuels for marine applications initiatives, MARAD tested the Navy hydrotreated algae-derived fuel blended to the HRD-76 and American Society for Testing and Materials (ASTM) D975-11 fuel specifications, and used ISO 8178 guidelines and MARPOL Annex VI NOx Technical Code for emission tests.

MARAD's objective was to ascertain the suitability of the blended renewable fuel for commercial marine operations. The project goals included:

- conducting limited operational, endurance, and exhaust emission tests of the test fuel underway at various loads up to full power and a prolonged pier-side operational test at a lower power,
- collecting and analyzing the operational, emission, and fuel consumption data; and observing engine conditions,
- testing the blending and density of the 50-percent neat renewable fuel with ultra-low sulfur diesel (ULSD) in a field environment, and
- evaluating the engine condition at the conclusion of the test, comparing it with the pre-test condition and also with the condition of similar engines with similar engine operating hours.

2.4 MARAD Algae-derived Fuel Test Background

Table 1 provides the list of vessels that MARAD submitted to the Navy for evaluation and selection.

Table 1. MARAD Ship Selection List

Name of the Vessel	STATE of MICHIGAN	49' Utility Boat	Pacific Queen	Bengamin Foss	Pacific Knight	Dorothy Sylvester	Buoy Tender	USACE S/V DOBRIN
Vessel Type	T-AGOS	BUSL	Tug	Tug	Tug	Crewboat	Utility	Survey
Operation (Cost/ Open sea)	Limited	Coastwise	Coastwise	Coastwise	Coastwise	Coastwise	Coastwise	20 miles Offshore
Owner	MARAD	USCG	FOSS	FOSS	FOSS	FOSS	NOAA	USACE
LxBxD in ft	224x43x20	49.17x16.83x?	73.3x26.3x11.4	73.3x26.3x11.4	73.3x26.3x11.4	52.6x14x7.5	?	65x18.75x9.5
Draft $_{max}$ in ft	14.92	5.92	11	11	11	7.5	?	3
Displacement, full load in LT	2262	35.92	276 ST	276 ST	276 ST	?	?	44.62
Service Area	Great Lakes	East Coast	Southern CA	Southern CA	Southern CA	Gulf Caribe	Great lakes	?
Home Port	Michigan	Connecticut?	LA/LB	LA/LB	LA/LB	LA	Michigan	New York
Date Built/Commissioned	1991	2000	1980	1980	1980	1963	1980	1998
Speed (Kts)	11	10	?	?	?	?	?	22.5
Fuel Tanks (#/capacity in gallons)	13/228,615	#/70,000	6/25,459	6/25,459	6/25,459	?/1,000	?/15,000	?/2,300
Day Tanks (#/Total capacity)	2/4,000 ea.	1/480(?)	2/?	2/?	2/?	2/?	2/500	?
Machinery:								
Config (# ME/# propulsion)	2/2	2/2	2/2	2/2	2/2	2/2	2/2	2/?
ME (#, Type)	CAT D-398	Cummins 6CTA8.3 MI	CAT D-398	CAT D-398	CAT D-398	John Deere 6125 12.5L	CAT 12V71 (2-stroke)	DD 12V-92TA
Rated HP	3200 (?)	305	2210	2210	2210	900	?	800
Max. ME RPM	1225	?	1,225	1,225	1,225	?	2400	2100
Specific fuel consumption gm/bhphr	?	?	?	?	?	?	?	?
Lube oil	Mobilgard 312	?	?	?	?	?	Bio-based	?
Propeller	2-Fixed	2- 4bladed	2- 4bladed	2- 4bladed	2- 4bladed	2- 4bladed	?	?

The vessel selected for the test program was the T/S STATE OF MICHIGAN, a retired Stalwart Class (T-AGOS 1) Modified Tactical General Ocean Surveillance Ship built by Tacoma Boat. The vessel was selected as the test platform for the following reasons:

- MARAD ownership, configuration, and availability control,
- similar engines to those currently used by the Navy, as the ship is ex-Navy vessel,
- fuel consumption was a reasonable match with the amount of fuel available from Navy,
- operated by Great Lakes Maritime Academy allowing an increased operational/testing window,
- electric propulsion for greater testing flexibility, and
- recent fuel tank cleaning and automation upgrade.

The vessel was commissioned in August 1985 as the PERSISTENT (T-AGOS 6) and was struck and transferred to GLMA in 2002 and renamed the T/S STATE OF MICHIGAN. The vessel is a diesel-electric drive vessel with four SSDGs and two propulsion motors. In 2009-2010, the control system was upgraded and the tankage was modified. Figure 2 shows the vessel.

The T/S STATE OF MICHIGAN has four main propulsion diesel generators that are electrically interconnected via a bus to drive two 800-hp propulsion motors and provide electrical power for the ship. Each propulsion diesel generator is a Caterpillar D398 engine with the following features:

- 12-cylinder, V-12, 4-stroke configuration,
- 6.25-inch bore, 8.00-inch stroke, 2,945-cu^3 displacement,
- 600 kW (800 hp) at 1200 rpm – fuel rate 47.6 gph, and
- turbocharged, aftercooled configuration.

The Navy currently uses this engine on its remaining T-AGOS 1 Class vessels in service as well as diesel generator service on some older ships in the fleet. Figure 3 shows the Caterpillar diesel generator engines. Figure 4 shows the engines as they are installed on the T/S STATE OF MICHIGAN.

Figure 2. T/S STATE OF MICHIGAN

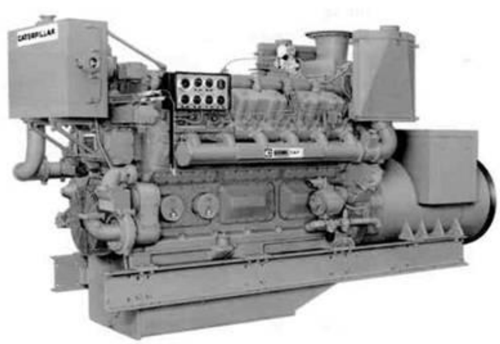


Figure 3. Caterpillar D-398 Generator Engines

Figure 4. T/S STATE OF MICHIGAN engine room

3. Test Program

Section 2.3 identifies MARAD's objective and goals for the test. To meet these goals, a test plan was developed. In June 2011 aboard the T/S STATE OF MICHIGAN, representatives from the Navy, MARAD, GLMA, EPA, NOAA, and USCG met to discuss a test plan. An overall approach to perform the testing to meet the goals was developed. The following sections discuss the test plan, preparation, and execution.

3.1 Test Plan

During the June meeting the T/S STATE OF MICHIGAN was selected as the test platform due to favorable characteristics of the ship and the increased testing/evaluation window offered by GLMA. Several key decisions were also made that formed the basis for the test plan. These were:

- Fuel supply system and tankage must have the ability to isolate ship service fuel tanks to successfully operate simultaneously using both the 50/50 blend test fuel and ULSD baseline fuel on different engines in the plant to ensure the vessel could safely be operated.
- Number 4 SSDG would be used for all testing including baseline ULSD emissions, 50/50 blend emissions, and 50/50 blend operational testing.
- Port Service Tank would be used to store and supply the 50/50 blend fuel and another storage tank would be used to store the extra 50/50 blend fuel needed for the balance of testing. The starboard service tank would be used to store the baseline ULSD.

One challenge with using the ship was the ability of the ship to get underway after August due to navigational and weather issues in the GLMA harbor area. There are operational restrictions to docking and undocking in the harbor, especially during periods of high winds and waves. The initial plan was to conduct all of the tests while underway, however, as the planning process continued, it was determined that a combination of underway and pier-side tests would be a better approach and actually enable the engine to operate for more hours on the alternate fuel. It was also determined that these extra hours of operation would be at lighter loads, which would provide another data point: performance on a lightly loaded engine.

The vessel's Chief Engineer estimated fuel-consumption as 35 to 40 gallons per hour during normal underway operations. MARAD prepared a set of options for underway and pier-side test combinations. Table 2 provides the operational options considered. Scenario Number 3, a combination of 17 days underway and 31 days pier-side, was selected. This alternative met the fuel requirements, provided the most achievable at-sea engine hours given weather/navigation concerns, and more closely matched the 50/50 blend fuel availability.

The alternative proposed 418 operational hours with an estimated fuel usage of 10,500 gallons. The fuel tank suction points would leave about 2,300 gallons of fuel in the two 50/50 blend fuel tanks that were used for service and storage. An additional 300 gallons of blend fuel was anticipated to be used to flush lines of ULSD and run in test engine before beginning fuel tests. As a result, the total fuel required was 13,000 gallons blend fuel. The Navy provided 6,500 gallons of neat HRD fuel to be blended with ULSD.

Table 2. Test Scenario Options

Test Scenario	Days		Hours		Total Number	
	Sea	Pier	Sea	Pier	Eng Hours	Fuel Consumption
1	5	61	50	488	538	11360
2	10	49	100	392	492	11040
3	17	31	170	248	418	10400
4	26	0	260	0	160	8320
Approximate per engine fuel consumption: Sea: 320 gal/day; Pierside: 160 gal/day Average day: Sea 10 hours; Pierside 8 hours						

The emissions part of the test plan was prepared in general terms by MARAD. The detailed emission test plan was prepared by UCR. The ISO 8178 D2 cycle profile was selected because of the engine is operated as a constant speed generator. One of the issues with the D2 cycle is the requirement of five test mode points ranging from 10 percent load to 100 percent load. Because all the generators are connected to a single electrical bus the middle points of operation are readily achievable. The 10 percent and the 100 percent test mode load points were difficult to achieve under operational restrictions. The 10 percent load is lower than the lowest load point for hotel load for the ship, which ranges between 12 – 16 percent of full load (MCR), with the propulsion motor disengaged. The 100 percent test mode load point was higher than the overload protection load point, which are restrictions programmed in control system that relate to single generator operation mode. The load limiter programming permitted 50 – 60 percent MCR maximum loading. The 25- 50-, and 75- percent MCR load mode points were achievable because of combinations of engines online and software programming. It was decided that for the 10 percent load point, an achievable and repeatable load point would be acceptable – 16 percent was chosen. A plan was developed to safely override the overload mode to allow for a 90 percent MCR load.

Section 3.2 describes other test preparations included in the test plan. These include the pre- and post-test inspection to establish the material condition of the engine before and after the test and to help determine the impact of the fuel on the engine. To perform the exhaust emissions tests, supplemental engine instrumentation including fuel flow meters and intake pressure and temperature gauges were installed and exhaust stack modifications were made. Finally the neat HRD fuel had to be mixed with the baseline ULSD fuel. This field blending was an essential part of the test plan as fuel delivery was a critical path item for the success of the project.

Appendix A contains the final test plan that was proposed to accomplish testing and achieve the objectives of MARAD and Navy. It also served as a planning document for GLMA to properly staff and crew the vessel for underway testing and support internal classroom scheduling since the ship also served as a floating classroom. As with any project, while some of the final details changed slightly from the original plan, the original plan is included in Appendix A and any alterations are noted in the following sections.

3.2 Test Preparation

Test preparation included pre-test engine inspection, engine and exhaust stack modifications, and fuel preparation. These activities had to be accomplished during the ship availability after the final at sea training mission run by GLMA. Activities were coordinated with GLMA personnel to ensure that all modifications were done in accordance with regulatory and classification body requirements. The exhaust stack modification required ABS approval.

3.2.1 Pre-Test Engine Inspection

Michigan Caterpillar provides engine maintenance for the T/S STATE OF MICHIGAN throughout the year and was selected to perform the inspection of the Number 4 SSDG prior to the start of the test. Caterpillar agreed to provide the same Field Representative who currently maintains the engine for the pre-test and post-test inspections as well as the two days of emission tests. MARAD developed a punchlist (Figure 5) of the minimal physical checks to establish the baseline material condition of the engine prior to the start of the fuel tests.

Caterpillar Pre-test Worklist

8/31/11

1. #4 engine: Pull out the fuel injectors and test for opening pressure and leakage. Reinstall the injectors.
2. #4 engine: Test/calibrate the fuel pumps on the engine.
3. #4 engine: Adjust inlet & exhaust valve timings.
4. #4 engine: Inspect the cylinders with boroscope when the injectors are removed for testing. Note the conditions.
5. #4 engine: Install fuel oil meters inlet and outlet to the engine. The meters should be recently calibrated by a recognized lab. with the calibration sticker affixed. The meter should preferably be accurate with a few % of the full flow rate of the fuel. Note: Need details on make, model, etc. of flow meters.
6. #4 engine: Install air mass flow/differential meter – not available, however, will install differential pressure and temperature gauges.

7. #4 engine: If possible, perform visual inspection of turbocharger (hot end) blades.
8. #4 engine: Change fuel filters
9. #4 engine: Take lube oil sample and send out for analysis.
10. #4 engine: Provide written details of results of Items 1, 2,3, 4, and 7. Also provide results of Item 9.

Figure 5. Caterpillar Punch List

Item 2 of the Punch List was omitted because the fuel pumps are combined Bosch pumps located in the center section of the engine between the cylinder heads. These types of pumps require removal from the engine and vessel for calibration which was beyond the scope of this project. All other items were accomplished. Items 5 and 6 are discussed in Section 3.2.2. Complete results are provided in Appendix B. A lube oil sample was drawn from the Number 4 SSDG sump and provided to Caterpillar for evaluation.

Caterpillar concluded that the condition of the engine was similar to that expected with an engine with similar use. The Number 4 engine had five of its twelve cylinders recently overhauled: #3, #5, #6, #7, and #8. Caterpillar was not able to procure a borescope with a camera to take pictures of the existing material condition prior to testing. Instead, a standard borescope was used. Post-inspection pictures were taken of the fuel nozzles when they were removed as were pictures of the turbocharger condition while the exhaust stack was removed.

3.2.2 Engine Instrumentation

The SSDG engine and generator package has a complete set of instrumentation installed to monitor adequately the performance during normal ship operations. In addition to the standard local operating panel shown in Figure 6, the engine room machinery control station has a microprocessor-based data collection and control station that digitally records the data and has trending and alarms. Figure 7 shows selected pictures of the machinery control station.

Figure 6. Engine Local Operating Panel

Figure 7. Engine Room Machinery Control Station

The instrumentation was adequate to monitor engine performance during normal operation, but the exhaust emission testing required the addition of some temporary instrumentation. Understanding of the intake air flow and fuel consumption is critical to exhaust emission calculations. To support these two data requirements, Caterpillar provided test instrumentation and installed taps into existing manifold and pipe systems.

Because of time limitations, Caterpillar was unable to provide an air flow measurement system. However, it was determined that the additional taps available in the intake manifold could be used to measure temperature and pressure. Figure 8 shows the taps and instruments that were installed in the engine manifold. A pressure gauge was installed in the inboard and outboard manifolds and a temperature probe was inserted in the inboard tap to support a local digital temperature gauge shown in Figure 9. Figure 10 shows the fuel meters that were inserted in the engine fuel supply and return lines. Figure 9 also shows the fuel meter that provided instantaneous fuel flows, total instantaneous engine fuel consumption, and cumulative fuel consumption. The equipment was used for the exhaust emission tests and the fuel meters were used for the entire test program to record fuel consumption. Appendix C provides more details about these instruments.

Figure 8. Intake Manifold Taps (Inboard left, Outboard right)

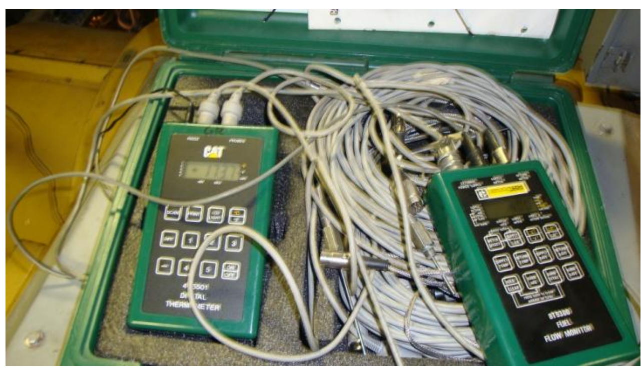


Figure 9. Temperature and Fuel Meters

Figure 10. Fuel Meters in Engine Fuel Supply and Return Lines

3.2.3 Exhaust Stack Modifications

To facilitate the insertion of the sampling probe for the exhaust emission tests, the exhaust stack of Number 4 SSDG was modified to insert a fitting into the exhaust trunk. This required design and drawing of a latrolet fitting insertion, submittal to American Bureau of Shipping (ABS) to obtain approval of the modification, gas free certification for hot work, and welding and hot work by ABS Certified welders to install the fitting. Appendix C provides all of the details of this effort including the ABS Certification. The resulting modification permitted the team to perform the exhaust emission testing. At the conclusion of testing, the fitting was plugged and lagged as it was not needed for the subsequent operational testing. Figure 11 shows the work that was completed prior to the beginning of the test. Additional work was performed to renew the stack condensate drain valve, which also was required for exhaust emissions testing.

Figure 11. Exhaust Trunk Modification

3.2.4 Fuel Preparation

The Navy provided the neat Algal-derived fuel. For current Navy testing, the fuel is blended with F-76 before shipping it out for testing. For this test, the plan was to provide the neat algal HRD fuel only to MARAD because the ship typically uses Ultra Low Sulfur Diesel (ULSD). ULSD was used both as a baseline fuel and the base petroleum fuel to blend with the HRD. The test required 6,500 gallons of algae-fuel and 11,500 gallons of ULSD (6,500 gallons for the blend and 5,000 gallons for the baseline testing and fuel requirements for the other engines for the duration of the blend fuel operational tests).

In order for MARAD to blend this fuel in the field two major concerns had to be overcome: lubricity and adequate blending of the two fuels. Lubricity is a concern with the algae-derived HRD (as with ULSD) fuel as it has a lower lubricity than is typically acceptable for marine power plants unless an additive is used. The Navy recommended a lubricity additive and the dosage requirements for both the ULSD and HRD. Field blending of the fuel to ensure the appropriate mixing of the algae fuel, ULSD, and lubricity additive is critical. Working with the fuel supplier, MARAD developed a blending methodology to mix and blend the fuels. Appendix D provides the details of the fuel mixing program as well as the density checks by a local test laboratory that were used to sample and test the density to ensure that the density was constant throughout the fuel before it was loaded. Figure 12 shows the mixing strategy used for this project.

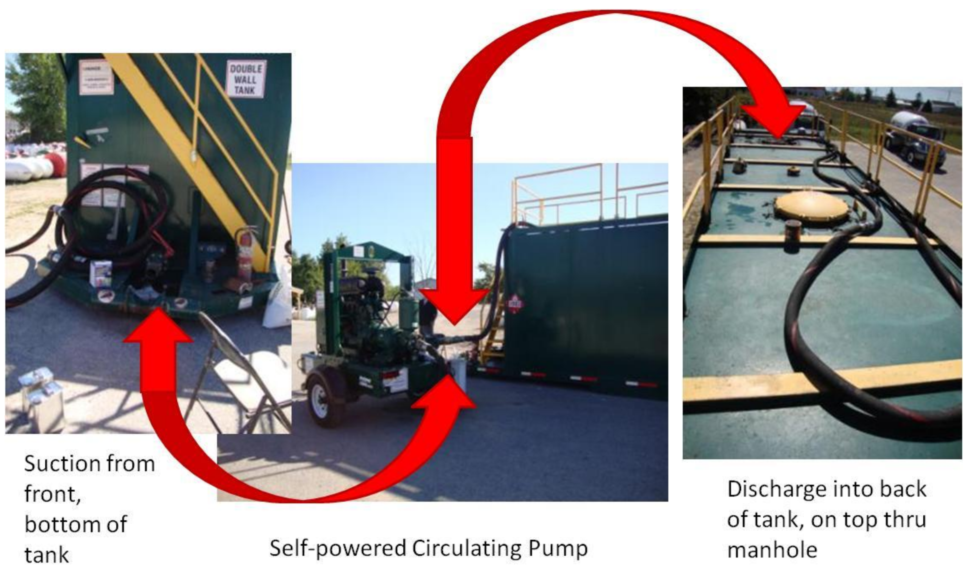


Figure 12. Fuel Blending Configuration at Fuel Provider Facility

Table 3 provides the characteristics of the baseline fuel. Additionally the Navy provided Certificates of Analysis for the fuel characteristics that are typically measured in the F-76 specification, which includes many of the tests performed in ASTM D975. Table 4 provides the basic fuel characteristics for the fuels MARAD used in the test.

Table 3. HRD Fuel Characteristics

Measured Properties	Units	Test Method	Specification Minimum	Specification Maximum	Measured Value
Flash Point	°C	D 93	60		78.0
Density at 15°C	kg/L	D 1298	0.774	0.876	0.7758
Total Water	ppm	D 6304		200	27
Particulate	mg/L	D 6217		1	0.9
Kinematic Viscosity at 40°C	mm²/sec	D 445	1.7	4.3	2.820
Distillation					
IBP	°C	D 86	Report		187.0
10%, (T10)	°C	D 86	191	290	248.5
50%, (T50)	°C	D 86	Report		280.0
90%, (T90)	°C	D 86	290	357	291.5
Final Boiling Point	°C	D 86	300	385	307.0
Residue + Loss	vol %	D 86		3	2.0
T50-T10	°C	D 86	Report		31.5
T90-T10	°C	D 86	20		43.0
Cetane Number or		D 613	42	80	> 74.7
Cetane Index		D 976	43	80	

Table 4. Baseline ULSD and Blend Fuel Characteristics

Test	Parameter	Method	Units	Minimum	Maximum	ULSD Fuel	50/50 Blend Fuel
Lubricity, HFRR	Wear Scar	D6079	µm		460	320	310
Appearance at 25°C		D4176	-----	Clear & Bright		Clear & Bright	Clear & Bright
Demulsification at 25°C		D1401	minutes		10	4	3
Density at 15°C		D4052	kg/m³			829	804
Distillation	10% Recovered	D86	°C	Report		205	218
	50% Recovered	D86	°C	Report		251	270
	90 % Recovered	D86	°C		357	310	297
	End Point	D86	°C		385	333	320
	Reside + Loss	D86	Volume %		3.0	1.5	1.6
Cloud Point		D5773	°C		-1	-18	-11
Color		D1500	-----		3	5.8	4.8
Flash Point		D93	°C	60		59	61
Particulate Contamination		D5452	mg/L		10	0.2	1.2
Pour Point		D5949	°C		-6	-27	-18
Viscosity at 40°C		D445	mm²/s	1.7	4.3	2.3	2.5
Acid Number		D974	mg KOH/g		0.30	0.05	0.06
Ash		D482	Mass %		0.005	0.001	0.000
Carbon Residue	10% Bottom	D524	Mass %		0.20	0.07	0.01
Copper Strip Corrosion at 100 °C		D130	-----		No. 3	1a	1a
Hydrogen Content		D7171	Mass %	12.5		13.6	14.1
Ignition Quality	Cetane Index	D976	-----	40		51	65
Storage Stability	Total Insolubles	D5304	mg/100 mL		3.0	0.6	0.2
Sulfur Content		D4294	Mass %		0.5	0.0	0.0
Trace Metals	Ca	D7111	mg/kg		1.0	0.0	0.0
	Pb	D7111	mg/kg		0.5	0.	0.0
	Na + K	D7111	mg/kg		1.0	0.3	0.3
	V	D7111	mg/kg		0.5	0.1	0.1

3.3 Test Execution

The original test plan comprised emission and operational testing. The operational testing was intended to be performed while the vessel was underway, however, as noted previously, the plan was subsequently modified to include a combination of underway and pier-side testing to accommodate the ship operations from a weather perspective. Table 5 provides the initial combination of days and hours. The 17 days of blended fuel operation included one day of emissions testing.

Table 5. Planned Test Execution

Test Day	Test Duration		Fuel (Gallons)	
	Days	Hours	Day	Total
Underway	17	168	320	5440
Pierside	31	248	160	4960
	48	416		10400

Appendix E provides the details of the test program execution, including the log sheets used for recording the test data. Table 6 summarizes the actual test execution in terms of hours and fuel consumed.

Table 6. Actual Project Operational Hours and Consumption

Test Day	Test Duration		Fuel (Gallons)	
	Days	Hours	Day (AVG)	Total
Underway	17	189.1	264.7	5455.7
Pierside	31	253.6	145.2	4500.5
	48	442.7		9956.2

3.3.1 Emission Testing.

The exhaust emission tests were conducted during the first two days of underway testing. The first day of emission testing was performed on the Number 4 SSDG using the baseline ULSD fuel. Upon successful completion of the emission test protocols using the baseline fuel, the ship's fuel transfer and supply system was realigned to run Number 4 SSDG on the blended fuel. The engine was switched over to the blended fuel for the remainder of the day as the ship returned to port. The second day of exhaust emission tests were run using the blended test fuel in Number 4 SSDG. This test day was counted as Day 1 of the 17 Underway Days. Appendix F provides the complete exhaust emissions test plan and test results report.

A major aspect of this project was the performance of exhaust emission testing conducted by UCR personnel from the College of Engineering Center for Environmental Research and Technology. The emission testing involved simultaneous measurement of NO_x, CO, O_2, and CO_2 from the No. 4 SSDG engine exhaust using an in-use Simplified Measurement Methods system that complies with the IMO NO_x Technical Code. International Organization for Standardization (ISO) methods were used to measure particulate matter (PM) mass and SO_x. To ensure the removal of any engine-to-engine variability, a single engine was selected for both the ULSD baseline and the 50/50 blend fuel emissions testing.

Because the Caterpillar D398 engines on this vessel are operated as generators for the electric motors, which propel the vessel, the appropriate test procedure for these engines is to operate according to the five modes of the ISO-8178-4 D2 cycle shown in Table 7.

Table 7. Standard Cycle for Testing Constant-Speed Engines

Mode	1	2	3	4	5
Speed	rated speed				
Load	100%	75%	50%	25%	10%
Weighting Factor	0.05	0.25	0.3	0.3	0.1

As configured, the control system for the SSDGs only permits the engines to operate at ~50 percent of their MCR of 600 kW to prevent overload. However, the control system designers indicated that this limiting function could be altered to allow the engines to operate at nearly 100-percent MCR. MARAD modified the control system accordingly for the emissions portion of the testing. With this change, the engine operated at ~92 percent of the MCR while the vessel operated underway on Lake Michigan. The achievable load points were determined at the time of testing and depended on several factors including constraints by current, wave pattern, and wind speed and direction. The emissions measurements were made as close as possible to loads and rpm specified in ISO 8178 D-2. As operated, the modes were at 92, ~81, ~61, ~27, and ~16 percent of the rated load for modes 1, 2, 3, 4, and 5, respectively (Table 8). The engine performance parameters measured or calculated for each mode during the emissions testing included engine speed, generator output, fuel consumption, cylinder exhaust temperatures, and air intake pressure and temperature.

Table 8. Emission Test Points

Fuel	Engine					
ISO 8178-4 D2	Load (%)	100	75	50	25	10
ULSD	Load (%)	92	82	60	26	17
ULSD	Load (kW)	554	490	359	159	101
Test Fuel	Load (%)	92	80	61	28	15
Test Fuel	Load (kW)	551	482	368	167	91

Measurement of Gaseous and Particulate Matter Emissions

The emission measurements were performed using a partial dilution system that was developed based on the ISO 8178-1 protocol. The gaseous and particulate emissions were measured using ISO 8178-1 and 2, and Chapter 5 of the NOx Technical Code, as they provide the general requirements for onboard measurements. The concentrations of gases in the raw exhaust and the dilution tunnel were measured with a Horiba PG-250 portable multi-gas analyzer. The PG-250 can simultaneously measure up to five separate gas components. The signal output of the instrument is typically interfaced directly with a laptop computer through an RS-232C interface to record measured values continuously. During the initial phases of equipment checkout, however, the computer stopped functioning, apparently because the electromagnetic frequency (EMF) from the generator corrupted the hard drive, and thus all readings

had to be recorded manually. Because all data is obtained under steady-state operating conditions, this did not present a major problem. Major features of the PG-250 include a built-in sample conditioning system with sample pump, filters, and a thermoelectric cooler. The performance of the PG-250 was tested and verified under the U.S. EPA Environmental Technology Verification (ETV) program.
Emissions were measured while the engine was operated at the test modes specified in ISO 8178-4 (Table 8). The measuring equipment and calibration frequencies met IMO standards. In addition to measuring criteria emissions, the project measured:

- PM continuously with a monitor to verify the PM concentrations remained constant while the filters were being loaded;
- PM mass fractionated into the elemental and organic fractions as an internal mass balance; and
- SO_x based on the fuel oil analysis.

Figure 13 shows a schematic of the sampling system for exhaust emission measurement equipment used. A properly designed sampling system is essential for accurate collection of a representative sample from the exhaust and subsequent analysis. ISO points out that particulate must be collected in either a full flow or partial flow dilution system: UCR chose the partial flow dilution system with single venturi (VN).

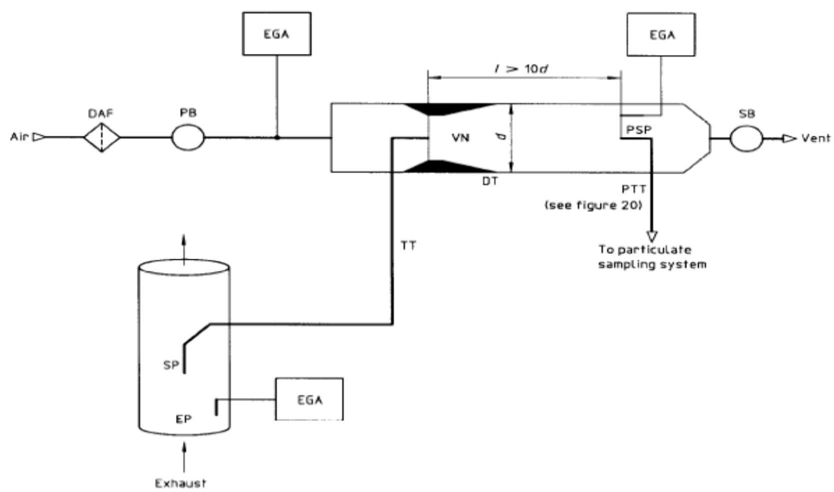


Figure 13. Partial Flow Dilution System

A partial flow dilution system was selected based on cost and the impossibility of a full flow dilution for "medium and large" engine testing on the ship and at the site. The flow in the dilution system eliminates water condensation in the dilution and sampling systems and maintains the dew point temperature of the diluted exhaust gas at <52°C before the filter sampling. ISO cautions that the advantages of partial flow dilution systems can be lost to potential problems such as: losing particulates in the transfer tube, failing to take a representative sample from the engine exhaust, and inaccurately determining the dilution ratio.

An overview of UCR's partial dilution system (Figure 13) shows that raw exhaust gas is transferred from the exhaust pipe (EP) through a sampling probe (SP) and the transfer tube (TT) to a dilution tunnel (DT) because of the negative pressure created by the VN in the DT. The gas flow rate through TT depends on the momentum exchange at the venturi zone and is therefore affected by the absolute temperature of the gas at the exit of the TT. Consequently, the exhaust split for a given tunnel flow rate is not constant, and the dilution ratio at low load is slightly lower than at high load. Thus, the apparatus used in this case eliminated the TT to prevent any inertial deposit of PM mass in the tube.

Calculation of Emission Factors

The emission factors at each mode were calculated from the measured gaseous concentration, the reported engine load in kilowatts (kW) and the calculated mass flow in the exhaust. An overall single emission factor representing the engine is determined by weighting the modal data according to ISO 8178-4 D2 requirements and summing them. The equation used for the overall emission factor is as follows:

$$A_{WM} = \frac{\sum_{i=1}^{i=n} (g_i \times WF_i)}{\sum_{i=1}^{i=n} (P_i \times WF_i)}$$

Where:

A_{WM} = Weighted mass emission level (CO, CO_2, $PM_{2.5}$, or NO_x) in g/kW-hr
g_i = Mass flow in grams per hour at the i^{th} mode,
P_i = Power measured during each mode, and
WF_i = Effective weighing factor. (1)

Calculation of the Exhaust Flow Rate by ISO 8178-1

The calculated emission factor depends strongly on the mass flow of the exhaust. Two methods for calculating the exhaust gas mass flow and/or the combustion air consumption are described in ISO 8178-1 Appendix A. Both methods, described below, are based on the measured exhaust gas concentrations and fuel consumption rate.

Method 1, **Carbon Balance**, calculates the exhaust mass flow based on the measurement of fuel consumption and the exhaust gas concentrations with regard to the fuel characteristics (carbon balance method). Based on procedures used for EPA and the Economic Commission for Europe (ECE) calculations, this method is only valid for fuels without oxygen and nitrogen content.

Method 2, **Universal, Carbon/Oxygen-Balance**, is used for the calculation of the exhaust mass flow when the fuel consumption is measurable and the fuel composition and the concentration of the exhaust components are known. It is applicable for fuels containing H, C, S, O, and N in known proportions.

The carbon balance method was ultimately selected for the study because it may be used to calculate exhaust flow rate when the fuel consumption is measured and the concentrations of the exhaust components are known. In this case, fuel consumption data was available. Flow rate is determined by balancing carbon content in the fuel with the measured carbon dioxide in the exhaust.

Calculation of the Exhaust Flow Rate

The assumption that the engine serves as an air pump for calculating exhaust flow rate in diesel engines, especially stationary diesel engines, is widely used. The flow rate is determined from the cylinder displacement and recorded rpm, with corrections for the temperature and pressure of the inlet air. It assumes that the combustion air flow equals the total exhaust flow. For low-speed, two-stroke engines, there could be scavenge air flow while the piston is on the expansion stroke and the exhaust valve is still open. This scavenge air would not be included in the air pump calculation, which leads to under-predicting the total exhaust flow and the emission factors. Thus, the method works best for four-stroke engines or for two-stroke engines in which the scavenge air flow is much smaller than the combustion air. This method was also selected for this study.

3.3.2 Underway Testing

Appendix E provides the details of the 17 days of underway tests performed. Each underway day included about 1-1/2 hours of operation to warm-up the engines and then undock and maneuver from the dock area out into Lake Michigan. During the undocking evolution three SSDGs (Number 1, 3 and 4) were online providing power to the main propulsion motors. Once the ship was in safe navigable waters the SSDGs were aligned according to the type of run that was to be accomplished. Table 9 provides the underway day profile information. Four separate operational profiles were accomplished during the underway testing. The ship's crew had the ability to mix and match underway days with pier-side days to accommodate weather and navigational concerns.

Table 9. Underway Test Day Details

	Test Duration		Fuel (Gallons)		Average	
Profile	Days	Hours	Day	Total	Hr/Day	Gal/Hr
Exh Emissions	1	11	305.0	305	11.0	27.7
Endurance Run	2	23.8	327.7	655.3	11.9	27.5
75 % MCR	13	143.2	323.2	4201.7	11.0	29.3
Special Run	1	11.1	293.7	293.7	11.1	26.5
Total	17	189.1		5455.7	11.1	28.9

Paragraph 3.3.1 describes the exhaust emission test profile used during the first underway test day. Three other test profiles were used for the remaining 16 underway days as follows:

- Endurance Run – This included changing the ship speed over a seven hour period to vary the load on Number 4 SSDG from 25 percent, 50 percent, and 75 percent MCR loads. Loadings from either SSDG 1 or 3 were combined to match the load requirements of Number 4 SSDG.

- 75 Percent MCR Run – This run included operating the ship at speeds associated with running the Number 4 SSDG at 75 percent MCR load for 7 hours. Either Number 1 or Number 3 SSDG was kept on idle standby throughout the run. The ship's crew had the latitude to vary the duration of the test if weather or other navigation concerns arose.

- Special Run – This final run was inserted at the request of the ship's crew. They were interested in obtaining operating information at 25, 50 and 75 percent MCR load points with three SSDGs online. This run also provided final season runs for Number 1 and Number 3 SSDG engines, which had been run at idle for significant periods of operation throughout the underway tests.

For all of these tests data were recorded by the engineering crew in forms found in Appendix E. Engine load, fuel consumption, and time of day were provided on an hourly basis.

3.3.3 Pier-side Testing

The balance of the operational testing was performed pier-side with the ship tied off. Pier-side operations were conducted for 31 days with operation of the Number 4 SSDG for eight hours per day providing power for the ship's hotel load. Each pier-side day started with a warm up of the Number 4 SSDG. Once the engine was sufficiently warmed up, shorepower was disconnected from the main breaker electrical bus and the Number 4 SSDG was put online. Typically the shorepower load is about 200 amps which is about 25 percent MCR load on the SSDG.

Table 10 provides a summary of the pier-side tests. For all of these tests data were recorded by the engineering crew in forms found in Appendix E. Engine load, fuel consumption, and time of day were provided on an hourly basis.

Table 10. Pier-side Test Details

	Test Duration		Fuel (Gallons)		Average	
Profile	Days	Hours	Day	Total	Hr/Day	Gal/Hr
Pierside	31	253.6	145.2	4500.49	8.2	17.7

4. Test Results

This section discusses the results of the test program and provides details of the engine inspections. Appendices F through H contain the complete exhaust emission report, complete post-test engine inspection results, and also post-test fuel and lube oil analyses, respectively. The next section summarizes the results, conclusions, and recommendations.

4.1 Emission Tests[2]

Appendix F contains the complete final exhaust emission test report as submitted by UCR. The graphs and results presented in this section are extracted from the body of that report. Figure 14 provides selected pictures from the emissions test configuration.

Figure 14. Emission Test Setup onboard T/S STATE OF MICHIGAN

The gaseous and PM emissions were measured in triplicate for each of the five modes of the ISO 8178-4 D2 test cycle. Table 11 shows a summary of the results of the exhaust emission tests provided in Table 5-1 of Appendix F. For each fuel, the emission measurements began when the engine was in stable operation at its maximum load (~100 percent). The load was then progressively reduced to ~75, ~50, ~25, and ~10 percent; as stable operation was achieved at each level, the emissions were measured. This procedure was repeated until three emission

[2] Data, tables, and information for this section extracted from report prepared by University of California, Riverside under MARAD Contract. UCR Report included in its entirety in Appendix F of this report.

measurements for each engine load were recorded. The exhaust flow rate was calculated using the Carbon Balance and "Air Pump" methods. The results are provided in Table 11.

Table 11. Emission Factor Test Results

	EFs (ULSD) g/kW-hr				EFs (Alt. Fuel) g/kW-hr				% Reduction			
	NO_x	CO	CO_2	$PM_{2.5}$	NO_x	CO	CO_2	$PM_{2.5}$	NO_x	CO	CO_2	$PM_{2.5}$
Exhaust flow rate calculated based on fuel consumption	7.9	1.44	866	0.104	7.1	1.19	822	0.078	10%	18%	5%	25%
Exhaust flow rate calculated based on intake manifold temp. & press.	7.6	1.37	827	0.098	6.9	1.15	798	0.075	9%	16%	4%	23%

One of the goals of the project was to measure the changes brought about by switching from a ULSD to a 50/50 blend test fuel. Table 11 shows that by the first method of calculating exhaust flow rate combustion of the 50/50 blend test fuel resulted in weighted emissions of NO_x, CO, and CO_2 were 10, 18, and 5 percent respectively lower than the emissions from the neat ULSD. This switch in fuel also caused significant reductions of 25 percent in the weighted emissions of $PM_{2.5}$. The second method of calculating exhaust flow showed reduced exhaust emissions only slightly lower than the first method. The 50/50 blend test fuel produces lower measured emissions of NO_x, CO, CO_2, and $PM_{2.5}$ relative to 100-percent ULSD. Figures 15 through 18 provide the data graphically.

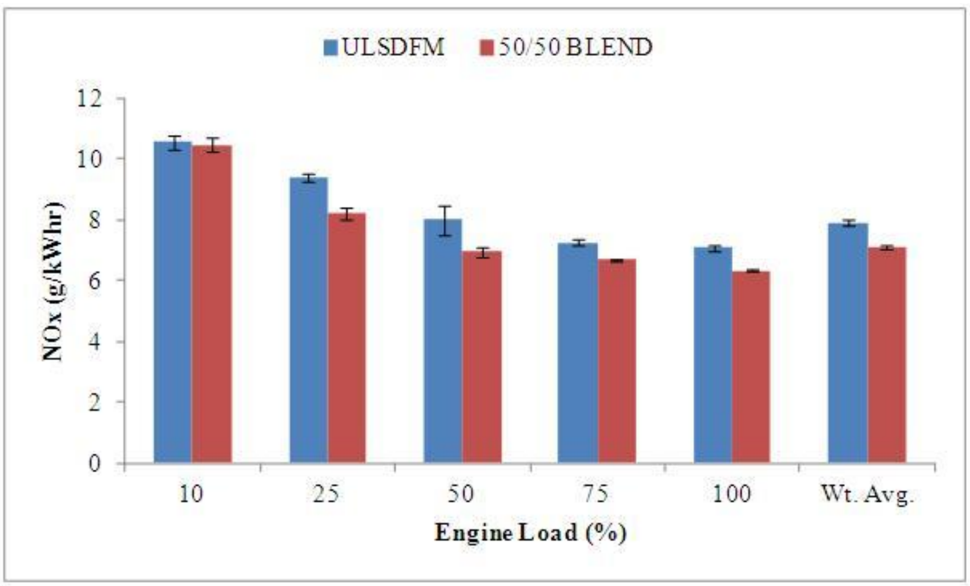


Figure 15. Average NO_x Emission Factors for each mode and Overall Weighted EF

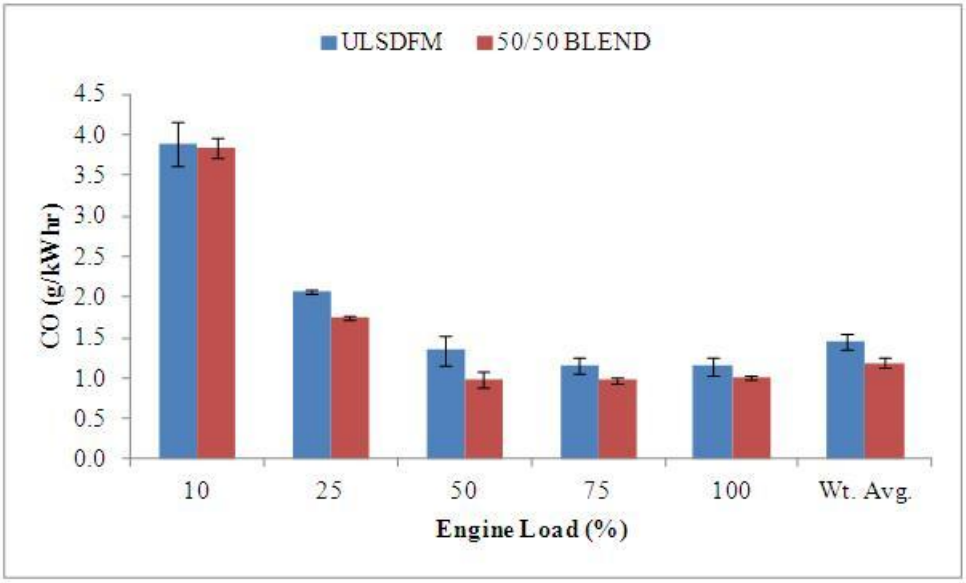


Figure 16. Average CO Emission Factors for each mode and Overall Weighted EF

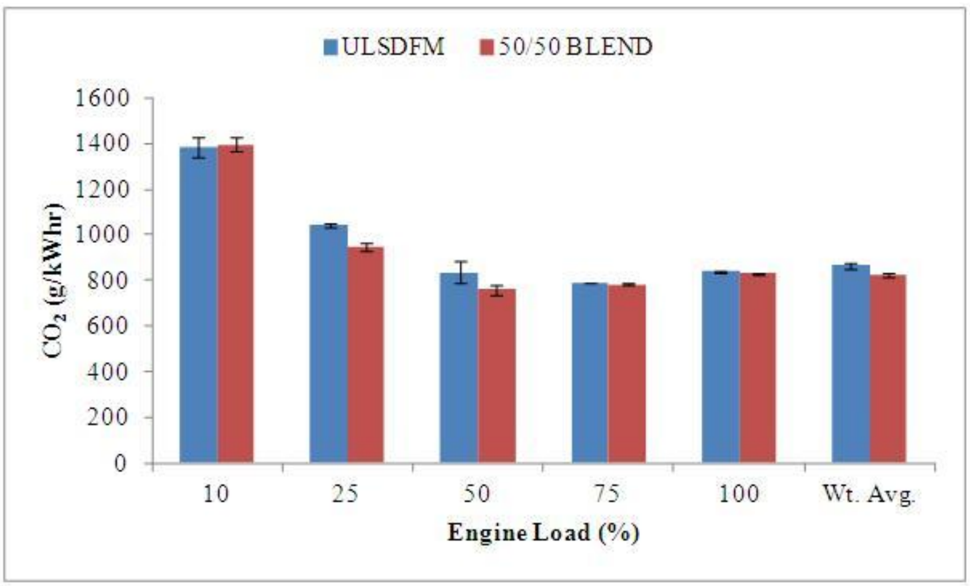


Figure 17. Average CO_2 Emission Factors for each mode and Overall Weighted EF

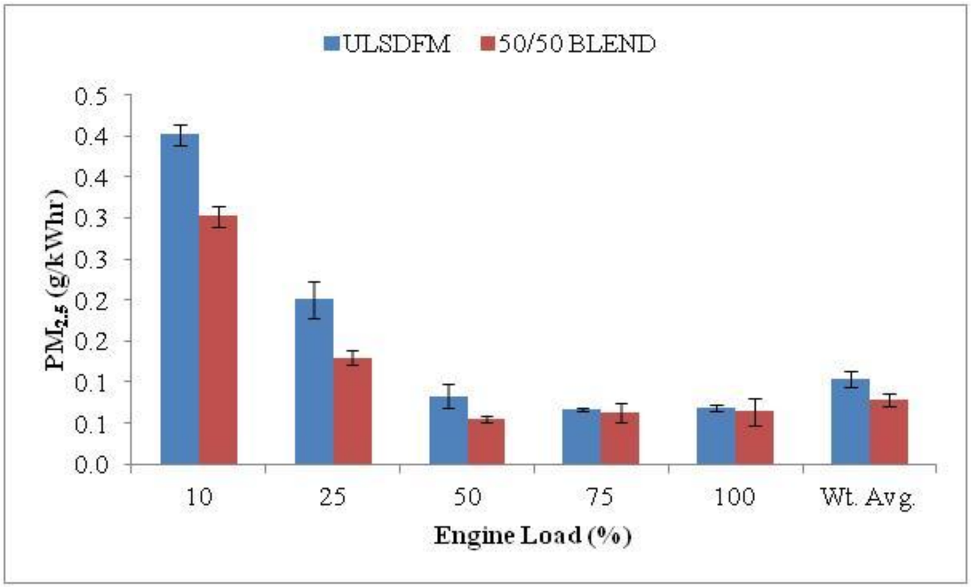


Figure 18. Average $PM_{2.5}$ Emission Factors for each mode and Overall Weighted EF

Figure 19 provides an overview of all of the emission factors and the effect of switching from ULSD to the 50/50 blend of ULSD and algal biofuel; Table 11 provides the average weighted emission factors. Table 5-1 in Appendix F provides the complete set of modal factors and the weighted factors shown in Table 11. Elemental Carbon (EC) and Organic Carbon (OC) are shown separately in Figure 19. With the exception of CO_2 at 16% engine load and OC at 92% engine load, all pollutants show a reduction by use of the 50/50 blend test fuel relative to ULSD. Based on the overlap of standard deviations for the averages, however, UCR concluded that the reductions were not statistically significant at engine loads of 81% and 92% for CO_2, $PM_{2.5}$, EC, and OC. UCR also concluded that at 16% engine load the reductions were not statistically significant for NO_x, CO, CO_2, and EC. At all other engine loads and for the weighted average load, the reductions were found to be statistically significant.

Emission of sulfur oxide (SOx) during combustion is also important. Paragraph 4.3.6 of Appendix F provides the methodology and calculation for determining SOx emissions based on ISO 8178-1 procedures. UCR assumed a sulfur content of 15 ppm for the ULSD and a sulfur content of 7.5 ppm for the 50/50 blend the maximum weighted emissions of SO_2 for the ULSD are 0.0080 g/bhp-hr and for the 50/50 blend they are 0.0038 g/bhp-hr, respectively. Subsequent analysis by NAVAIR determined, through testing the sulfur content using ASTM Method D5453 (Appendix D), that the initial value of sulfur for the baseline ULSD was 10.3 ppm while the 50/50 blend was 3.9 ppm. So the actual weighted SO_x emissions of both fuels is 0.0055 g/bhp-hr and 0.0020 g/bhp-hr, respectively, which is less than what was predicted by UCR.

A secondary objective of UCR's emission testing was to determine the effect on fuel consumption by switching from ULSD to the 50/50 blend of ULSD and algal biofuel. Table 12 provides the fuel consumption and percent reduction by switching to the 50/50 blend fuel. Figure 20 shows this same information graphically. UCR determined that while the differences are statistically significant for the 28%, 61%, and weighted average points, the reductions were not statistically significant at the 16%, 81% and 92% points. UCR concluded that the majority of the fuel consumption benefits were for intermediate loads where the engines spend a significant amount of time under normal operating conditions.

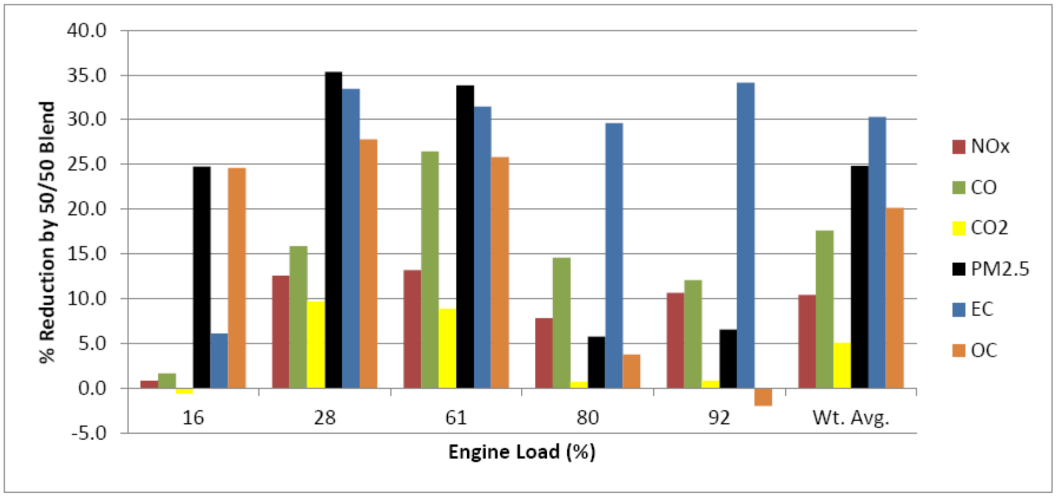


Figure 19. Percent Reduction in Pollutants by 50/50 Blend

Table 12. Fuel Consumption and Percent Reduction by 50/50 Blend

Engine Mode	Engine Load (ULSD)	Engine Load (50/50 Blend)	Fuel Consump-tion (ULSD)	Fuel Consump-tion (50/50 Blend)	% Reduction
	(%)	(%)	g/kW-hr	g/kW-hr	
100	92	92	265	264	0.3%
75	82	80	249	249	0.2%
50	60	61	263	241	8.4%
25	26	28	330	300	9.2%
10	17	15	438	443	-1.2%
Average Weighted Fuel Consumption			273	261	4.5%

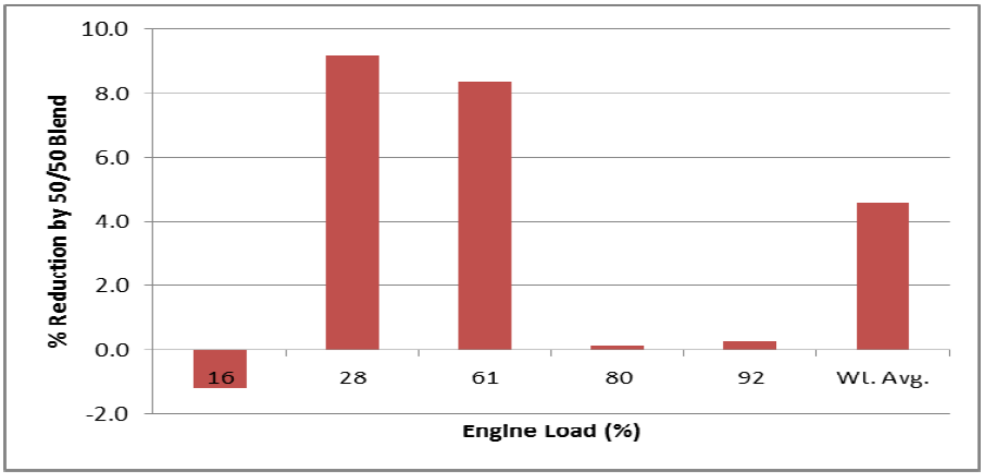


Figure 20. Percent Reduction in Fuel Consumption by 50/50 Blend

4.2 Post-Test Diesel Inspection

Paragraph 3.2.1 provided the details of the pre-test engine inspection. The same Michigan Caterpillar Service Representative performed both inspections of the Number 4 SSDG. The punchlist (Figure 21) indentifies the physical checks that would establish the material condition of the engine after completion of the fuel tests and provide a comparison to the initial pre-test condition. Item #3 was not performed as it was not accomplished in the initial test. The additional optional inspections of Number 1, 2, and 3 SSDGs were performed.

Caterpillar Post-test Worklist

Date: 11/28/11

1. #4 engine: Pull out the fuel injectors; visually inspect condition and test for opening pressure and leakage. Reinstall the injectors upon completion of borescoping.
2. #4 engine: Remove inspection crankcase covers and visually inspect with borescope the condition of cylinders liners.
3. #4 engine: Test/calibrate the fuel pumps on the engine.
4. #4 engine: Inspect and photograph the cylinders with borescope when the injectors and crankcase covers are removed for testing. Note the condition. Crank engine and observe inlet/exhaust valve condition. Need borescope with photographic capability. Ensure all photographs clearly depict wear pattern of liner liners, liner honing markings, piston wear pattern, and upper end landing.
5. #4 engine: Adjust inlet & exhaust valve timings.
6. #4 engine: Remove fuel oil meters inlet and outlet to the engine and replace with flexible hose provided by ship.
7. #4 engine: Remove intake manifold taps and reinstall pipe plugs.
8. #4 engine: If possible, perform visual inspection of turbocharger (hot end) blades. Use borescope with camera.
9. #4 engine: Change fuel filters
10. #4 engine: Take lube oil sample and send out for analysis.
11. #4 engine: Replenish oil level and provide replacement for oil used during test
12. #4 engine: Provide written details of results of Items 1, 2, 3, 4, and 7 including all photos taken during Item 3 and 7. Also provide results of Item 9.

Optional

1. #1, #2, and #3 engine: Open up two (2) power packs per engine, as designated by pulling out fuel injectors from the corresponding power packs on each engine; visually inspect condition and test for opening pressure and leakage. Reinstall the injectors on completion of Optional Item 2.
2. #1, #2, and #3 engine: Inspect and photograph the cylinders with borescope when the injectors are removed for testing. Note the condition of the cylinder liners. Crank engine and observe inlet/exhaust valve condition for each cylinder, including the underside of the cylinder heads. Need borescope with photographic capability. Ensure all photographs clearly depict wear pattern of liner liners, liner honing markings, piston wear pattern, and upper end landing.
3. #1, #2, and #3 engine – Take lube oil sample and send out for analysis
4. Provide written details of results of Items 1 and 2 including all photos taken for all three engines. Also provide results of Item 3.

Figure 21. Caterpillar Punch List

Complete results of the post-test inspections are provided in Appendix G. The fuel filters were changed at the end of the test. A lube oil sample was drawn from the Number 4 engine sump and provided to Caterpillar for evaluation.

4.2.1 Fuel Injector Test Results.

All 12 fuel nozzles were removed from Number 4 SSDG for testing and to facilitate the borescoping. Figure 22 shows a new nozzle tip that was pulled out of spares. Figure 23 shows a complete nozzle assembly that is inserted into the cylinder head. The black portion of the assembly connects to the high pressure fuel supply tube. Figure 24 shows the internal parts that make up the fuel nozzle. Each nozzle comes as a preset, pretested unit that is set to the correct pop (point at which injector nozzle begins to spray fuel) pressures at the factory. There are no adjustments possible within the nozzle. The injectors nozzles from the Number 4 SSDG (Figure 25) were visually inspected and determined to be in good condition and consistent with the condition of injectors with similar hours of operation. Figure 26 provides a visual comparison of the nozzle tip condition of a typical nozzle from Number 4 SSDG and the nozzle from Cylinder Number 9 of the Number 2 SSDG, which was not operated during this entire test but has about as many hours on it as Number 4 SSDG had before the test started. The new nozzle tip is shown as reference.

Figure 22. New Nozzle Tip

Figure 23. Nozzle Assembly

Figure 24. Nozzle Cutway

Figure 25. Post-Test Condition of Number 4 SSDG Nozzle Assemblies

Figure 26. Nozzle Tip Comparison

Each of the fuel nozzles were pop tested and pressure tested in a portable pressure test rig provided by Caterpillar. Figure 27 shows the portable test rig that was used during the pre- and post-test nozzle testing. Table 13 provides the comparison results for the nozzle test from the pre- and post-test provided by Caterpillar. The results indicate that there was no noticeable difference in nozzle performance between the start of the test and the finish. The leakage pressure tests yielded similar acceptable results. Based on these results and the results of the visual inspections, Caterpillar determined that this renewable fuel has no detrimental effect on the fuel injection nozzles.

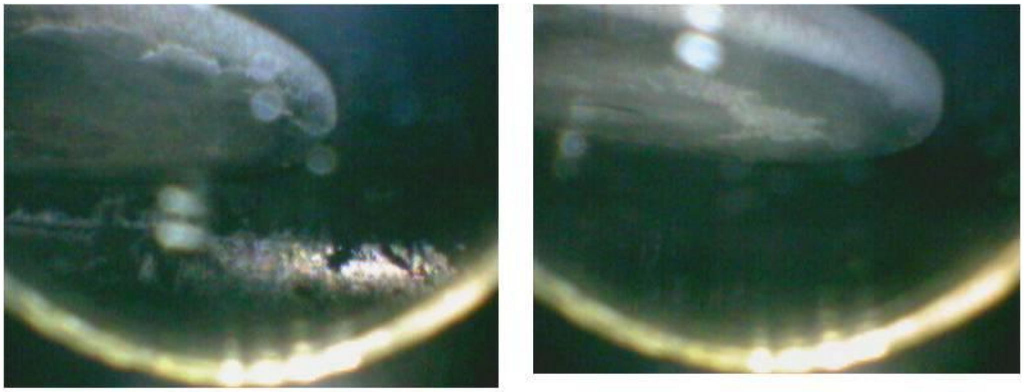
Figure 27. Nozzle Spray and Pressure Test – (spray/pop test shown at right)

Table 13. Nozzle Test Results

Cylinder	Valve opening pressure (psi)		Spray pressure (psi)		Spray pattern		Pressure held for 30 seconds (psi)	
	Pre-Test	Post-Test	Pre-Test	Post-Test	Pre-Test	Post-Test	Pre-Test	Post-Test
1	450	450	500	500	good	good	300	300
2	450	450	475	475	good	good	300	300
3	475	475	500	500	good	good	400	400
4	475	475	500	500	good	good	350	350
5	475	475	500	500	good	good	350	350
6	475	475	500	500	good	good	350	350
7	475	475	500	500	good	good	450	450
8	525	525	550	550	good	good	400	400
9	500	500	525	525	good	good	350	350
10	490	490	525	525	good	good	300	300
11	480	480	500	500	good	good	300	300
12	475	475	500	500	good	good	300	300

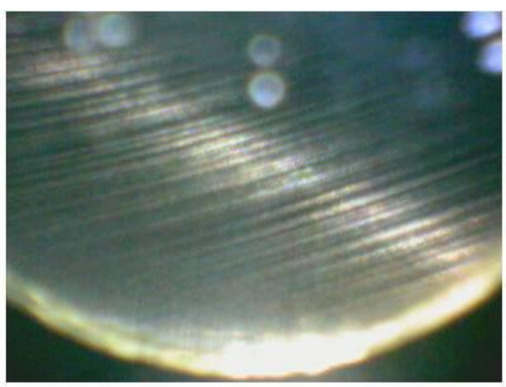
4.2.2 Cylinder Condition Assessment

Appendix G provides complete results of the cylinder condition. The post-test inspection included complete cylinder borescoping as well as removal of the crankcase inspection cover from the fourth and sixth cylinders of Number 4 SSDG. The results of the visual borescope inspections yielded no abnormal or visible changes from the initial inspection. Unfortunately as mentioned previously, a borescope with a camera was not available during the pre-test inspection so comparison pictures are unavailable. However, the service representative was able to take pictures during the post-test borescope inspection. Figure 28 shows some typical pictures taken from the post-test borescope inspections. Figure 29 shows the lower end picture from cylinder Number 6.



Typical Valve Crown Condition

Typical Exhaust Valve Typical Inlet Valve



Typical Liner Hone Marks

Figure 28. Typical Borescope Pictures

Figure 29. Cylinder Number 6 -Lower End Hone Marks

4.2.3 Turbocharger Condition Assessment

The condition of the turbocharger is usually a good indicator of how clean a fuel combusts. The turbochargers in this engine were photographed pre-test with a camera and photographed using the borescope post-test. Appendix B and Appendix G contains all of the photos taken of the turbocharger. Figure 30 and 31 show the pre-test and post-test blade conditions, respectively. Caterpillar found the condition of the turbocharger blades consistent with an engine that has run on traditional fuels with this many hours.

Figure 30. Pre-Test Turbocharger Condition

Figure 31. Post-Test Turbocharger Blade Condition

4.2.4 Valve Lash Adjustment

Caterpillar measured the cylinder intake and exhaust valve backlash. Each cylinder has one intake and exhaust valve. These measurements are consistent with how there were set during the pre-test inspection. Table 14 shows the result of the post-test measurement of the backlash.

Table 14. Nozzle Test Results

Cylinder	Valve Lash (in)	
	Intake	Exhaust
1	0.015	0.037
2	0.015	0.036
3	0.018	0.035
4	0.015	0.036
5	0.015	0.036
6	0.015	0.036
7	0.015	0.035
8	0.016	0.036
9	0.015	0.035
10	0.015	0.036
11	0.016	0.035
12	0.016	0.035

4.3 Post-Test Fluid Analysis

As part of the performance assessment, Post-Test analyses of the test fuels and lube oil were performed. Appendix H contains the entire results of this testing. Additionally, the fuel oil filters were pulled and replaced. They were visually inspected and appeared normal. There was no increase in filter differential pressure or abnormal fuel system pressures indicated throughout the test. As a follow on test, the U.S. Coast Guard prepared a test plan to evaluate the long term storage of the fuel. The test required the transfer of all of the ULSD test fuel and blend test fuel into "winter storage" tanks on the port and starboard sides of the ship. This test was started at the conclusion of the post-test inspection and will conclude in April 2012. While MARAD had planned to test the fuel and lube oil at the end of test, the fuel biological contamination test was added. This test is discussed in Paragraph 4.3.2.

4.3.1 Fuel Specification Test

Fuel samples were drawn from the fuel transfer lines during the transfer of fuel to the final winter storage tanks. The samples were sent to NAVAIR for testing similar to that performed during the fuel preparation (Paragraph 3.2.4) for the project. The two Certificates of Analysis (ULSD and blend fuel) are provided in Appendix H. The fuel test results were consistent with the initial pre-test results.

4.3.2 Fuel Biological Contamination Test Results

For the follow-on test, the U.S. Coast Guard prepared a test plan to evaluate the long term storage of the fuel. This test plan included a baseline assessment of the microbiological contamination of the fuels before they were put into storage for winter. This baseline will then be compared with the results of a similar test performed at the end of the test period in April 2012. Appendix H contains the results from the initial test. Figure 32 shows the test kit and Figure 33 shows the results from the test. Appendix H also contains the technical guidance for reading the MicrobMonitor kit. It should be noted that all of the comparator photos are provided to indicate a fuel phase test volume sample of 0.25ml. The kit does allow for a 0.5 ml fuel sample option, which was chosen as the test sample. While the blend fuel shows an indication of biological contamination, it is considered within the normal range based on the volume of the sample size. This contamination could have resulted during a number of operations including the movement of the fuel within the ship's fuel transfer system, and the storage and service tanks used during the tests. The tests to be conducted in April 2012 should provide a good indication whether any additional microbiological growth has occurred.

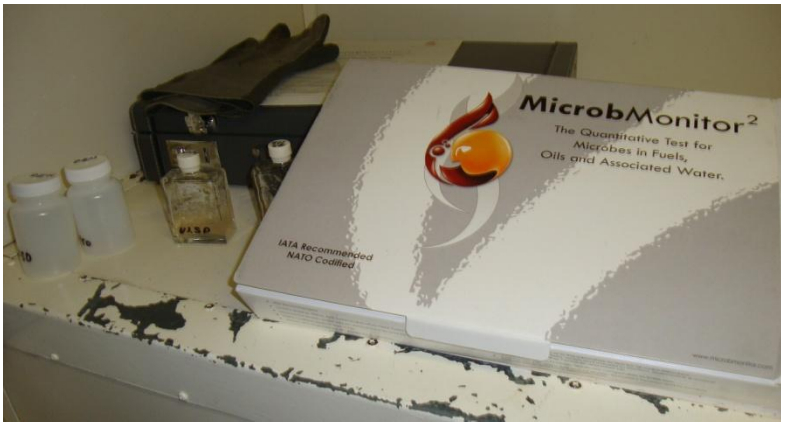


Figure 32. Biological Contamination Test Kit

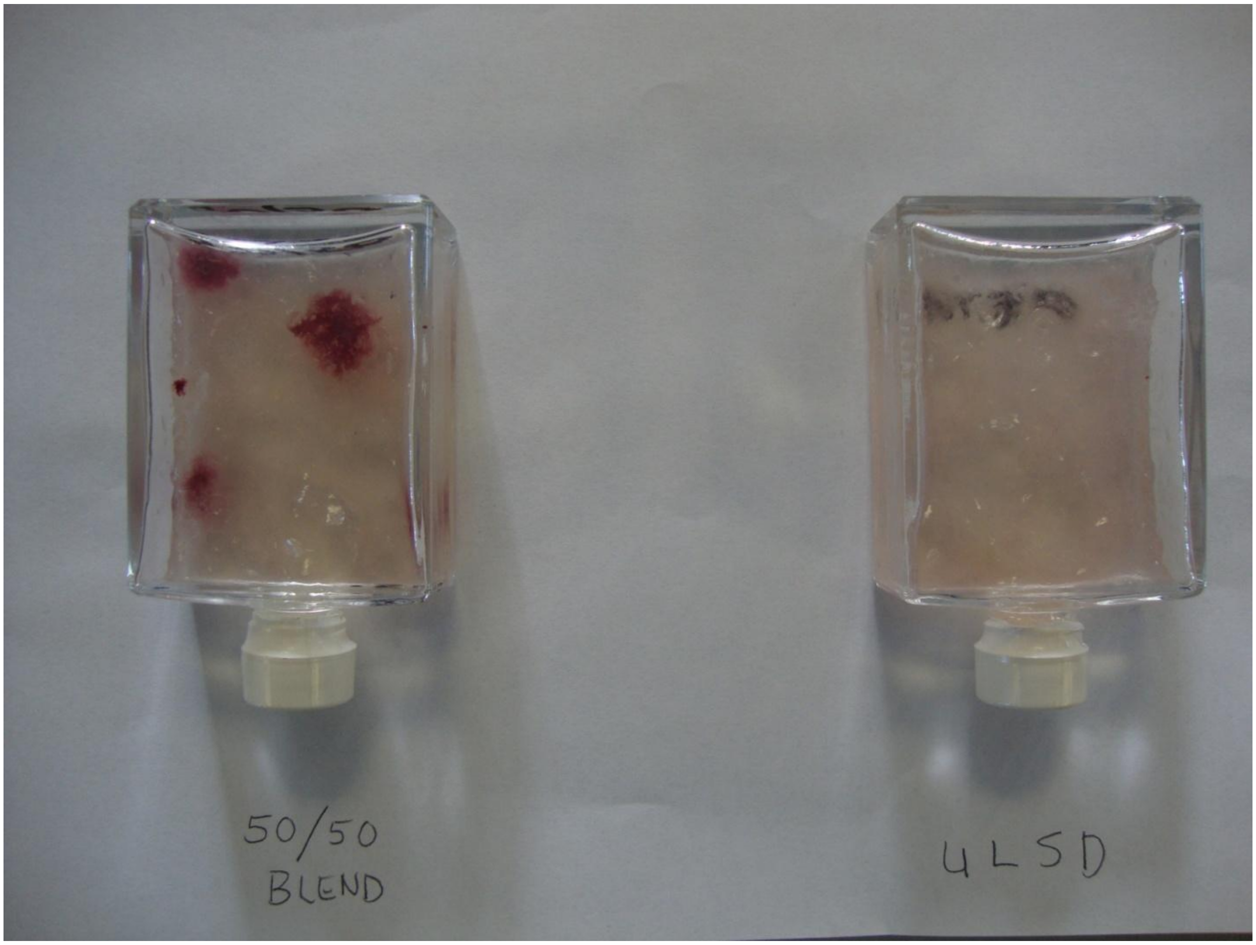


Figure 33. Biological Contamination Test Kit

4.3.3 Lube Oil Analysis

Lubricating oil samples were taken prior to the start of testing, at the start of testing, after the underway testing was completed, and at the end of test. The lube oil sample taken prior to the start of testing was sent to the Joint Oil Analysis Program Laboratory, which is run by the U.S. Navy. The results of the tests indicated the lube oil was within normal limits. At the start of the blend fuel tests, a sample was drawn by Caterpillar and sent to its laboratory for analysis. Samples drawn at the end of the underway and pier-side tests were collected by the Ship's crew and submitted to Caterpillar's test laboratory. The initial two samples showed normal levels but the final sample indicated the possibility of fuel dilution per Caterpillar. The test results show NEG for fuel dilution for all tests performed, however, the viscosity difference indicated that there may be some slight dilution. As a result, Caterpillar took an additional sample for analysis. These results also indicated the possibility of fuel dilution problems by viscosity, but still showed negative for fuel dilution. Caterpillar indicated that fuel dilution is typical for this type of engine as the nozzles can have loose tolerance and leakage occurs. Further, the removal of fuel nozzles for borescoping most likely added to the observed fuel dilution problem in the lube oil. It should be noted that other engines on this ship have had fuel dilution problem. The test plan called for the lube oil to be changed out: this will occur during the next few months. Appendix H contains the Lube Oil reports.

5. Conclusions and Recommendations

The main objective of this project was to test an HRD fuel, currently being tested by the U.S. Navy for consideration as a "drop-in" fuel, in a commercial type shipboard application. MARAD specifically designed a test plan to evaluate the 50/50 blend of ULSD and Algal HRD fuel to determine whether it is acceptable for commercial marine use. Accomplishing this objective required a comparison of emissions and operational performance of the 50/50 blend test fuel with the baseline ULSD, and an assessment of the blended fuel and its impact on the engine.

The current Navy HRD test program includes a complete Qualification Protocol including property testing, component and full-scale engine tests, and platform testing. The Navy plans to test a Green Strike Group of ships in summer 2012. The Navy has also provided MAERSK Lines (a commercial shipper) with some HRD fuel. MAERSK tested this fuel on a container ship using an auxiliary diesel generator and special tankage and piping.

While many tests have been performed on first generation Fatty Acid Methyl Ester (FAME) biodiesel fuels, the opportunity for MARAD to test a second generation HRD renewable fuel onboard a ship was an important milestone given the various drawbacks of the first generation biofuels. Although the Navy is laboratory testing the fuel on diesel engines as part of the Qualification Protocol, this was the first full-scale ship platform test of the HRD renewable fuel in a shipboard diesel generator over multiple days of operation with pre- and post-test material condition assessments, performance, endurance and emissions testing. The test plan also provided an opportunity to determine the feasibility of field blending smaller quantities of fuel as well as delivery and shipboard storage and transfer. Also because the T/S STATE OF MICHIGAN is a T-AGOS 1 Class ship it has engines that are still in active use in MARAD, NOAA, and Navy vessels.

The Number 4 SSDG was used for the baseline and blend fuel exhaust emission testing and also for the remainder of the testing. Testing commenced on 10 September 2011 and was concluded 17 November 2011. After 17 underway days and 31 pier-side test days of operating Number 4 SSDG engine on the 50/50 blend fuel, the engine was inspected and found to be in good operational condition. The Number 4 SSDG was operated for over 440 hours on the test fuel. The engine consumed about 9,500 gallons of the test fuel over this span of time. The remaining 3500 gallons were transferred into a storage tank and will be part of an ongoing U.S Coast Guard/MARAD long-term storage stability test to be completed in April 2012.

Modifications to the exhaust stack were accomplished to accommodate the exhaust emission test equipment.

Exhaust Emission Impact

Exhaust emission testing was performed while underway on Lake Michigan using the baseline ULSD and then the 50/50 blend fuel on two consecutive days. A detailed test profile for emission testing was developed to comply with the test protocol of ISO 8178 D2 cycle. The same profile was run using both fuels. Emission tests were performed by UCR for a period of two days at the start of the test. The same generator engine was used for both fuels.

The UCR report concludes that the 50/50 blend test fuel produces lower measured emissions of NO_x, CO, CO_2, and Particulate Matter (PM). ISO 8178 calls for the measurement of exhaust emissions at five test points and then using the defined weighting factors a weighted emission factor is created. The weighted emission of NO_x, CO, and CO_2 were 10, 18, and 5 percent lower respectively for the 50/50 blend test fuel than for same engine operated on the ULSD. The switch in fuel also resulted in a 25 percent reduction in the weighted emissions of PM and a lower volumetric fuel consumption for the same power output.

These results indicate that if a 50/50 blend of this HRD and ULSD were made available to the commercial marine marketplace at a similar delivered price to ULSD, lower emissions would be achieved. Most significant would be the reduced PM, which is currently a major clean air issue. Likewise, the reduced greenhouse gas emissions would slightly reduce the carbon footprint of a vessel that used this fuel.

Material Condition Inspection

Underway and Pier side operations were also run to accumulate the necessary engine operating hours to evaluate the impacts of the fuel on the engines. Post testing, the engine conditions were assessed using a combination of visual inspection and testing and compared to the initial pre-test engine inspection. The conclusion of the Service Representative was: "After all the inspections were done I did not see anything abnormal. The effects of the biofuel were the same as running on Number 2 ultra low sulfur diesel."

After review of the operating data, material condition reports, and from onsite observation, it appears that the 50/50 blend test fuel appeared to perform better than neat ULSD. Visual inspection of exhaust emissions from the SSDGs operating at the same load, emission from Number 4 SSDG appeared to be clearer than that of the others. The engine parts examined were in a condition consistent with engine parts of a similar engine age. This leads to the conclusion that after over 440 hours of operation at various engine loads there is no indication of any adverse effect of the fuel on the engine and fuel systems.

The long-term stability test will be concluded in April 2012. The test results are encouraging and MARAD believes that the 50/50 blend test fuel used for this test would be an acceptable drop-in replacement fuel to replace ULSD that is used on the T/S STATE OF

MICHIGAN and more broadly on other commercial vessels with this type of engine. The testing successfully demonstrated all facets of drop-in fuel performance – from fuel husbandry (loading, transferring, and supply to the engine) to superior exhaust emission performance. Addition of the HRD to the ULSD also provided an improvement in heating value which resulted in slightly better fuel consumption performance as well.

This project provided valuable performance data and results suggesting that further drop-in fuels testing would be advantageous since the Number 4 SSDG exhaust stack abroad the T/S STATE OF MICHIGAN has been permanent modified and baseline data has been gathered, the ship makes a particularly good platform for future testing of fuels.