Appendix F

Technology Evaluation

Feasibility of Using Existing Emission Control Technologies for Marine Applications

In this appendix, brief descriptions of NOx and PM emission reduction control strategies currently used in general diesel engine applications will be presented. Some of the control technologies presented have been recently introduced to use in the marine environment. Staff believes many of the control technologies presented here can be used in the marine environment, but, at this time, there are no control technologies that have been verified for marine applications through the ARB verification procedure. Descriptions of a number of demonstrations of different control technologies are provided in this appendix.

There are a number of control technologies that have been proven to reduce emissions of oxides of nitrogen (NOx) and particulate matter (PM) from diesel-fueled engines used in on-road, and off-road, applications. While, in theory many of the control technologies used in land-based applications could potentially be marinized to work in the marine environment, the potential success of these methods when applied to marine vessels will be highly dependent on the specific application. Considerations for applicability include the engine duty cycle, engine placement in the hull, vessel exhaust system configuration, and age of the vessel. Since most marine vessels are custom built and have vastly different engine room configurations with varying capacity for space in which to install after-treatment emission controls, it is unlikely that there will be “off-the-shelf” or “one size fits all” aftertreatment devices available for ocean going vessels. It is likely that the control devices will also need to be customized to each vessel configuration. Nevertheless, we believe that over the next several years, there will be increased desire to develop control technologies for marine applications to help mitigate the emissions that occur in and around ports and urban centers.

Although there have been only a limited number of demonstration projects for emission control techniques used on ocean-going vessel engines, there has been more testing of emission-control techniques on harbor craft engines, specifically on ferries. These engines, however, are generally much smaller than those used on ocean-going ships.

Diesel PM Exhaust After-treatment Emission Controls

The principle exhaust treatment technologies that have been successfully used to reduce diesel PM from diesel-fueled engines used in land-based applications are diesel particulate filters (DPF), diesel oxidation catalysts (DOC), and flow through filters (FTF) (or combinations of technologies). Each of these is briefly described below.

Diesel Particulate Filters

DPFs have been successfully used in many applications, including stationary prime and emergency standby generators, and with both on-road and off-road engines. In general, a DPF consists of a porous substrate that permits engine exhaust gases to pass through but traps the diesel PM. DPFs can reduce diesel PM emissions by more than 85 percent. The magnitude of these emission reductions depends on the baseline emissions of the associated engine, and the fuel sulfur content. In addition, up to a 90 percent reduction in carbon monoxide (CO) and a 95 percent reduction in hydrocarbons (HC) can also be realized with DPFs. (Allansson, 2000) Most DPFs employ some means to periodically regenerate the filter, i.e., burn off the accumulated PM. In California, diesel-fueled school buses, emergency backup generators, solid waste collection vehicles, urban transit buses, medium-duty delivery vehicles, people movers, and fuel tanker trucks have been retrofitted with DPFs. These installations have been implemented through a number of voluntary and regulatory mandated programs as well as demonstration programs. DPFs can be either active or passive systems.

An active DPF uses a source of energy beyond the heat in the exhaust stream to induce regeneration. Active DPF systems can be regenerated with an electric current passed through the substrate, fuel burners, microwaves, or the aid of additional fuel injection to increase exhaust gas temperature. Some active DPFs induce regeneration automatically when the vehicle or equipment reaches a specified exhaust back pressure. Others simply indicate when to start the regeneration process. Other active systems collect and store diesel PM over the course of a full day or work shift and are regenerated at the end of the day or shift when the vehicle or equipment is shut off. A number of the smaller filters are then removed and regenerated externally at a "regeneration station." Because active systems have control over their regeneration and are not dependent on the heat in the exhaust, active DPFs have a much broader range of applications and a much lower probability of plugging than passive DPFs.

A passive DPF is one in which a catalytic material is applied to the substrate. The catalyst materials used are known as the platinum group metals. These consist of platinum, iridium, osmium, palladium, rhodium, and ruthenium. Platinum is best suited as the catalyst for diesel engine control devices; therefore, it appears that it will be the main catalyst used in diesel catalytic converters. (Kendall, 2002/2003) The catalyst allows trapped PM to oxidize at lower temperatures which are periodically achieved in diesel exhaust. No additional source of energy is required for regeneration, hence the term "passive."

Field experience indicates that the success or failure of a passive DPF is primarily determined by the exhaust temperature profile at the filter's inlet and the rate of PM generated by the engine. These two parameters, however, are determined by a host of factors pertaining to both the details of the application, the duty cycle, the level of engine maintenance, and the type of engine being used. As a result, the technical information that is readily accessible can serve as a guide, but it may be insufficient to determine whether a passive DPF will be successful in a given application. (ARB, 2002)

With regard to estimating average exhaust temperature in actual use, commonly documented engine characteristics such as the exhaust temperature at peak power and peak torque are insufficient. The exhaust temperature at the DPF's inlet is highly dependent on the particular duty cycle and plays a prominent role, as does heat loss in the exhaust system. Various application-specific characteristics enter the heat loss equation, such as the length of piping the exhaust must travel through before it reaches the DPF and whether the exhaust is “wet cooled” or “dry cooled”. Lower average exhaust temperatures can also be the result of operating engines oversized for the application or engines operating with low or no load applied. (ARB, 2002)

Diesel Oxidation Catalysts

DOCs are currently the most commonly used form of diesel after-treatment technology and have been used for compliance with the PM standards for some on-highway engines since the early 1990s. DOCs are generally referred to as “catalytic converters.” DOCs are attached to the engine exhaust system. Chemically-lined substrates catalyze the oxidation of carbonaceous pollutants – some of the soot emissions and a significant portion of the soluble organic fraction. These carbon-containing pollutants are oxidized to carbon dioxide (CO_2) and water.

DOC effectiveness in reducing PM emissions is normally limited to about 30 percent of diesel PM because DOCs only control the soluble organic fraction (SOF) of diesel PM. For modern diesel engines, this is typically less than 30 percent of the total PM. Additionally, DOCs increase sulfate PM emissions by oxidizing the sulfur in fuel and lubricating oil, reducing the overall effectiveness of the catalyst. Limiting fuel sulfur levels to 15 ppm allows DOCs to be designed for maximum effectiveness (nearly 100 percent control of SOF emissions). DOCs also reduce emissions of HC and CO with reported efficiencies of 76 percent and 47 percent respectively. (Khair, 1999)

DOCs are also very effective at reducing the air toxic emissions from diesel engines. Test data shows that emissions of toxics such as polycyclic aromatic hydrocarbons can be reduced by more than 80 percent with a DOC. (DieselNet, 2002)

Flow-Through Filters

Flow through filter (FTF) technology is a relatively new technology for reducing diesel PM emissions. Unlike a DPF, in which only gasses can pass through the substrate, the FTF does not physically "trap" and accumulate PM. Instead, exhaust flows through a medium (such as wire mesh) that has a high density of torturous flow channels, thus giving rise to turbulent flow conditions. The medium is typically treated with an oxidizing catalyst or used in conjunction with a fuel-borne catalyst. FTFs reduce emissions of PM, HC, and CO. Any particles that are not oxidized by the FTF flow out with the rest of the exhaust and do not accumulate.

The filtration efficiency of an FTF is lower than that of a DPF, but higher than a DOC. In addition, compared to DPFs, the FTF is much less likely to plug under unfavorable conditions such as high PM emissions, low exhaust temperatures and emergency circumstances. The FTF, therefore, is a candidate for use in applications that are unsuitable for DPFs.

Sea Water Scrubber

The technology of sea water scrubbing has been used for many years to reduce SOx and PM emissions from oil and coal burning power plants on land where it is more commonly referred to as flue gas desulfurization (FGD). The FGD process exposes the exhaust gases to alkaline sorbent slurries or solutions containing lime ($Ca(OH)_2$), limestone ($CaSO_2$), lye (NaOH), or magnesium hydroxide ($Mg(OH)_2$) which absorb the SOx. FGD using sea water as the scrubbing agent has also been utilized for years to produce inert gas for use aboard tankers. (EPA 2003)

The sea water scrubber utilizes the naturally occurring calcium carbonate in the sea water as the reagent to remove up to 95% of the SOx, 50-80% of the PM and approximately 10% of the NOx from the ship's engine exhausts.

Several stages of raw sea water and gas mixing occur to ensure high levels of scrubbing efficiency. The scrubbing cools and entrains droplet of sea water. A demister is installed to prevent these droplets of sea water from being carried out in the exhaust after the final stages of scrubbing. After the cooled exhaust gas passes through the demister, which eliminates the free water, it is reheated in a hot air injection manifold. This reheating process changes the relative humidity of the gas from 100% to 80%.

The wash water effluent from the scrubber flows from the scrubber unit to a wash water treatment plant which consists of a series of multicyclones designed to separate particles from the wash water. Additional sea water, which is naturally alkaline, is then added to the separated wash water in order to raise the pH to near neutral prior to discharge. (Holland, 2007)

NOx Emission Controls

There are various technologies available and in development to provide reductions in NOx. The principal technologies are selective catalytic reduction (SCR), water injection, exhaust gas recirculation, NOx adsorbers, and lean NOx catalysts. These are each briefly described below.

Selective Catalytic Reduction

SCR is an exhaust after-treatment method for controlling NOx emissions up to 90 percent. The SCR process basically works by injecting ammonia (NH_3) or urea into the exhaust gas or the engine in the presence of a catalyst. Ammonia reduces NOx in the presence of the catalyst to produce nitrogen (N_2) and water.

SCR systems have been installed on new marine engines for many years. However, retrofitting SCR systems on existing vessels is challenging. The challenging issues include urea and ammonia storage, safety requirements, and space requirements near the engine. The SCR system is only effective at exhaust temperatures of 270℃ or above. Ammonia sl ip can also be a problem if the system is not properly optimized. (DieselNet, 2006a) Ammonia slip is caused by injecting more ammonia into the exhaust stream than is needed to reduce the NOx.

Water Injection

Adding water to the combustion chamber absorbs heat when the water vaporizes, lowering the peak combustion temperatures and reducing NOx emissions. Water can be introduced in a variety of ways: direct water injection, fumigation into the intake air, or emulsified with the fuel. Unmodified engines can use emulsified fuel if the injection systems can handle the extra volume. Other systems require major redesign to include separate water supply tanks, injection lines, fuel pumps, injectors, etc. Generally, a 1 percent increase in water equates to a 1 percent decrease in NOx emissions. However, HC and CO emissions may increase using water injection strategies. (DieselNet, 2006)

Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) lowers combustion temperatures thereby reducing NOx formation. EGR displaces some of the engine's intake air with inert materials, which dilute the mixture in the cylinder and absorb heat. PM in the exhaust has the potential to be a source of problems with EGR, including accelerated wear in the engine and turbocharger, and deposition on the engine intake system, which can decrease the effectiveness of the turbocharger and/or aftercooler. By reducing combustion temperatures and available air for combustion, EGR may cause incomplete combustion, increases in HC, CO, and PM emissions, and decrease fuel economy. (DieselNet, 2006)

NOx Adsorber

NOx adsorbers utilize materials which store NOx under engine lean conditions, then release and catalytically reduce the stored NOx under engine rich conditions.

The process entails oxidation of NO to NO_2, usually using a platinum-based catalyst, then oxidizing it again and storing it as a metallic nitrate on the catalyst surface. The most common storage component is barium carbonate ($BaCO_3$), which can store NO_2 as barium nitrate ($Ba(NO_3)_2$) while releasing CO_2.

The NOx adsorber is regenerated by operating for a brief period in an engine rich condition. NOx is released and subsequently reduced by precious metal catalysts just as a three-way catalyst does today on modern automobiles. NOx reductions can be in excess of 90 percent if the catalyst is well matched to the exhaust temperature profile. (EPA, 2004)

There are also diesel fuel reformers available that regenerate and desulfinate the NOx adsorption catalyst. The process consists of an electrically generated plasma and a noble metal catalyst that converts a diesel/air mixture into a hydrogen rich gas. Based on the partial oxidation process, carbon atoms from the fuel are oxidized to CO and the hydrogen is released as hydrogen molecules. This hydrogen rich diesel reformate provides a reducing atmosphere, improves NOx adsorption and catalyst regeneration, reduces the temperature at which desulfation occurs, and reduces the fuel penalty. (Bromberg, 2003)

Lean NOx Catalyst

Lean NOx catalysts reduce nitrogen oxides through selective catalytic reaction with hydrocarbons. NOx conversion is usually limited to about 10-20 percent due to the relatively low concentrations of hydrocarbons in diesel exhaust. In active lean NOx catalysts, where diesel fuel is injected upstream of the catalyst, NOx conversions of up to 50-60 percent are possible. Conversion rates are dependent on exhaust temperatures. (DieselNet, 2006a)

Engine Design Modification

There are a number of engine modifications that can be employed, generally at the time of an engine rebuild, to reduce emissions. Two examples of engine design modifications that reduce PM emissions are a diesel engine reengineering kit produced by Clean Cam Technology (Clean Cam) and the ECOTIP Superstack Fuel Injectors (ECOTIP) distributed by Interstate Diesel.

Clean Cam consists of specific engine retrofit components, including a proprietary camshaft. The product reduces NOx emissions by increasing the volume of exhaust gas that remains in the combustion chamber after the power stroke. Within the combustion chamber, the residual exhaust gas absorbs heat and reduces the peak combustion temperature, which results in lower NOx emissions. The injection timing can then be adjusted (i.e., advanced) to maximize the diesel PM emission reductions or it can be varied to achieve the desired balance of NOx and PM. The Clean Cam reduced diesel PM and NOx emissions from eleven pre-1993 and four 1994-2000 models of two-stroke diesel-fueled engines manufactured by Detroit Diesel Corporation (DDC). The ARB has pre-certified Clean Cam technology. Clean Cam's Version 2 of the camshaft kit can reduce NOx emissions up to 10 percent beyond the U.S. EPA's Tier 2 Off-road engine NOx emission standards and can reduce PM emissions by 75 percent beyond the U.S. EPA's Tier 2 Off-road engine PM emission standards, depending on the engine's horsepower rating.

Interstate Diesel takes a different approach with the ECOTIP Superstack Fuel Injectors to reduce emissions from existing engines. This product has been shown to reduce diesel PM emissions from engines manufactured by Electro-Motive Division (EMD). The product consists of a fuel injector with a reduced sac [DEFINE SAC] volume and a more consistent fuel injection pressure, compared to average engines. The product improves combustion and reduces diesel PM emissions by minimizing the amount of fuel that drips into the combustion chamber at the end of the fuel injection cycle. The ECOTIP fuel injectors can provide a 2 to 3 percent fuel savings, depending on engine load. The manufacturer states that the overall diesel PM emission reduction can be up to 44 percent. The product is commercially available and has been installed on diesel generator plants, locomotives, and tugboats. (Interstate Diesel, 2006)

Injection timing retardation

Retarding the injection timing has been used for decades for reducing NOx. The effect of injection retardation is to reduce the maximum combustion pressure and hence temperature. A reduction of up to 30 percent can be achieved by this technique however, a penalty of up to 5 percent in standard fuel consumption results, as the engine efficiency is reduced. Increase in injection pressure is used in conjunction with injection timing retard to maintain fuel consumption. Another modification that is used when implementing this strategy is a modification of the engine's compression ratio.

Combinations of Technologies

Combinations of more than one technology are also being explored to maximize the amount of diesel PM reduction. For example, fuel-borne catalysts can be combined with any of the three main hardware technologies discussed above: DPF, FTF, or DOC.

Shore-Based After-treatment System

A bonnet is placed over the vessels exhaust stack to capture the emissions. Exhaust gases are channeled to a cloud chamber scrubber and SCR. Since SCR efficiency is temperature dependent, the gases may require reheating to a minimum of 280℃ when using marine diesel oil (MDO) and 290℃ when using heavy fuel oil (HFO) with a sulfur content of less than 1%. Depending on the fuel used by the auxiliary engines the combination of the scrubber and SCR are reported to remove up to 97% of the NOx, 97% of the SOx and 92% of the PM from the vessel's exhaust gas. (ACTI 2006)

Portable Distributed Generation

These systems consist of a turbo charged generator encased in a specially made container and mounted on the back of a trailer. The trailer can be repositioned to accommodate varying vessel sizes and configurations. A separate liquid natural gas (LNG) or propane tank trailer supplies fuel to the engine. The system is designed to provide electricity to the vessel in either 50Hz or 60Hz frequency and multiple voltages to supplement or in lieu of the power generated by the ship's auxiliary engines. (Wittmar 2006)

Cleaner Diesel Fuels, Alternative Diesel Fuels, and Alternative Fuels

Diesel PM emission reductions can also be achieved through the use of cleaner diesel fuels, alternative diesel fuels, or alternative fuels (e.g., compressed natural gas). Some marine vessel owner/operators have explored the use of alternative diesel-fuels with some success and others have tried using compressed natural gas, however, there are some limitations when using alternative diesel fuels and alternative fuels. Below we describe some fuel options for marine engines.

<u>Alternative Diesel Fuels</u>

Alternative diesel fuel can be used in a diesel engine without requiring engine or fuel system modifications for the engine to operate, although minor modifications (e.g., recalibration of the engine fuel control) may enhance performance. Examples of alternative diesel fuels include biodiesel, emulsified fuels, Fischer-Tropsch fuels, or a blend of these fuels with CARB diesel fuel. A detailed discussion of these fuels is provided in the Diesel Risk Reduction Plan. (ARB, 2000) These alternatives may result in significant benefits for higher-emitting applications. Synthetic or alternative diesel fuels may also prove to be part of the preferred control strategy for diesel-fueled engines that would otherwise expose people to relatively high risk, or where control retrofit options are very expensive or difficult to implement. The impacts these fuels can have on emissions from diesel-fueled engines can vary. There has not been significant penetration of these fuels into commercial marine engine applications, however biodiesel is being used with some success in some ferries and recreational boats. (von Wedel, 1999; Biodiesel.org, 2006)

<u>Alternative Fuels</u>

Alternative fuels may be an option to reduce emissions from diesel engines, but use of these fuels in marine applications is not as prevalent as in land-based applications. Use of alternative fuels in marine vessels presents a variety of safety issues that the U.S. Coast Guard must address before vessels can be converted so they can use alternative fuels. The passenger ferry *James C. Echols* in Norfolk, Virginia was converted from diesel to compressed natural gas (CNG) fueled twin Caterpillar 3406-G natural gas engines in 1995 and was emissions tested in 2002. The natural gas engines ran richer than optimum, and adjustments to the fuel-air ratio resulted in a reduction in power. (Wilcox, 2000; Thompson, 2002) The concept of using vent gas from the boil-off of liquefied natural gas (LNG) carriers to fuel propulsion and auxiliary engines has been employed in a Gulf Coast shrimp boat by converting the engines to use CNG. LNG is bunkered and converted to CNG fuel through boil-off before use. (Wilcox,- 2000; Acker, 1989)

Repowering

Repowering (i.e., replacing the engine) can be a viable and cost-effective way to reduce emissions when compared to the older, uncontrolled diesel engines they replace. Heavy-duty diesel engines currently being manufactured are significantly cleaner than those built just a short time ago and can provide significant NOx and PM benefits compared to an older engine. (DieselNet, 2002a)

Fuel Cells

Fuel cells have captured worldwide attention as a clean power source and have generated interest and enthusiasm among industry, enviromentalists, and consumers. In principle, a fuel cell operates like a battery. A fuel cell converts chemical energy directly into electricity by combining oxygen from the air with hydrogen gas. However, unlike a battery, a fuel cell does not run down or require recharging. It will produce electricity as long as fuel, in the form of hydrogen, is supplied. Fuel cells have been a reliable power source for many years.

In-Use Experience with Diesel PM and NOx Emission Control Strategies on Marine Vessels

Demonstration Projects:

There have been a number of demonstration projects nationwide funded primarily through public agencies to implement installation of aftermarket emission controls for marine vessels. The alternative emission control strategies used in these demonstration projects represent the range of choices a vessel owner/operator has when deciding whether to use an after-treatment devices to reduce emissions from their vessel. Brief discussions of some of these demonstration projects are presented below. Most of these projects are primarily with harbor craft engines, but a few have been conducted on ocean-going vessels.

Diesel Particulate Filters

<u>U.S. Navy Workboat</u>

In 2006, one of two early 1970's two-stroke Detroit Diesel Corporation (DDC) 12V-71 400 horsepower engines on a U.S. Navy workboat operating in the Suisun Bay was rebuilt. The port engine was rebuilt with Clean Cam Technology System (CCTS), The CCTS engine rebuild replaces the original cam shaft, updates the cylinder liner configuration, and adds a turbocharger to the engine. This rebuild kit's purpose is to reduce NOx and PM emissions from a variety of DDC engines during the normal rebuild cycle.

In addition to the engine rebuild, a Rypos active diesel particulate filter replaced the traditional exhaust muffler. The Rypos diesel particulate filter (DPF) consists of a filter housing, electrical control circuit, and filter cartridges.   The Rypos system does not rely on high exhaust gas temperatures for filter regeneration; instead a controller monitors pressure, initiating regeneration when needed. The filters are made of sintered metal, which can be heated electrically for filter regeneration.

The preliminary emissions tests results for each diesel emission control strategy and combined are as follows. The rebuilt CCTS engine reduced PM emissions by over 30 percent and NOx by approximately 70 percent. The Rypos filter achieved a reduction of PM of approximately 70 percent and a small reduction of NOx. Used together, the CCTS and Rypos active DPF achieved over 80 percent reduction of PM and over 70 percent reduction of NOx. Durability testing of the system was completed in late 2006. To date, we have not received the results of those tests.

Sea Water Scrubber

Holland America Line is conducting a seawater scrubber feasibility project aboard the MS Zaandam in 2007-08 with the assistance of EPA/West Coast Collaborative and Puget Sound Clean Air Agency grants.

The sea water scrubber system was scheduled to be installed in April 2007 with operation and testing of the system from May 2007 to October 2008. Results are scheduled to be reported in mid to late October 2008. (Holland, 2007a)

The same company that manufactured the sea water scrubber system for the *MS Zaandam* also installed a similar system on the ferry *M/V Pride of Kent* in the United Kingdom in 2005. (Holland, 2007)

Selective Catalytic Reduction

<u>Vallejo Ferry</u>

In 2004, the City of Vallejo, California, launched the M/V Solano, a low emissions ferry utilizing urea-based selective catalytic reduction (SCR) made by Steuler GmBH. This ferry is part of the Vallejo Baylink passenger ferry system, which services Vallejo and the North San Francisco Bay. The ferry has two MTU/DDC 16V-4000 engines with rated power of 3100 hp each. The SCR system is designed to reduce NOx by 57 percent. (Baylink, 2006; MARAD, 2003)

In July of 2007, Baylink was experiencing an increase in engine problem alarms. BayLink staff inspected the engines and the SCR unit. They found that a number of the engines in the starboard unit were showing excessive wear. They also examined the starboard SCR unit and found extensive damage. The damage to the SCR unit included corrosion, heat impacts, and mechanical impacts. The

Baylink staff has published a report and continues to look into the potential reasons for the damage to the engine and the SCR unit. (Baylink, 2007)

Staten Island Ferry

Staten Island Ferry (M/V Alice Austen) was retrofitted with selective catalytic reduction and a diesel oxidation catalyst in 2004. The ferry is propelled by two Caterpillar 3516 1,550 horsepower main engines. The system reduces NOx by 50 percent as well as PM by 25 percent. With adjustments to temperature thresholds and one of the main engines rebuilt, the anticipated NOx reduction is about 70 percent. (Bradley, 2006)

The Alice Austen has been operating with SCR since 2005. The vessel is in service during the night runs of the Staten Island Ferry system (9 p.m. to 5 a.m.). A complete circuit of the route the vessel is assigned to takes about an hour. The vessel idles for about 15 minutes during passenger off- and on-loading, makes a twenty minute run to the route's destination, idles for 15 minutes to off-load and on-load passengers, and makes a twenty minute run back to its point of origin. To date, there have been no problems with the SCR system.

San Francisco Bay Area Water Transit Authority (WTA) Ferry

WTA is planning to build two new 149 passenger ferries to be put into service in late 2008 which will include exhaust aftertreatment to reduce NOx emissions by at least 85 percent beyond Tier 2 standards. The ferries are being designed to incorporate a compact SCR system coupled with an oxidation catalyst with the 1410 hp Detroit Diesel propulsion engines. The inclusion of the aftertreatment system will require about six feet to be added to the vessel's overall length. The system was derived from one that has been used on other mobile equipment. The ferries' design includes a dry exhaust with a high exhaust stack.
(WTA, 2006)

Container Ship *Sophie Maersk*

In 2005, a urea-based SCR was installed on auxiliary engine #5 of the container ship *Sophie Maersk*. The University of California Riverside's Bourns College of Engineering, Center for Environmental Research and Technology (CE-CERT) in association with Maersk and CARB, conducted the testing using a partial dilution system conforming to ISO 8178. NOx and PM were measured at engine loads of 25 percent, 50 percent and 75 percent on three separate dates using both HFO and MDO.

The NOx reductions averaged 90 percent at the three test loads using HFO and there were no PM reductions. The NOx reductions averaged nearly 100 percent at the three test loads using MDO, but the ammonia slip was high at 10 to 70 ppm. The PM reductions averaged approximately 60 percent when using MDO. (Maersk, 2007)

Water/Fuel Mixture

San Francisco Bay Area Water Transit Authority Ferry

In 2003, the San Francisco Bay Area WTA partnered with the Golden Gate Bridge, Highway and Transit District, to test PuriNOx™, a water and diesel emulsion, on the ferry *M/V Golden Gate*. The 28-year-old ferry is powered by two 671-hp Caterpillar 3412C turbocharged and after-cooled diesel engines. Its fuel tanks were cleaned, and for 11 weeks it ran on PuriNOx™ fuel instead of conventional diesel fuel. No filter fouling was observed. The fuel emulsion remained stable in the fuel tanks. Because emission testing was conducted during periods of passenger service, test points were limited to full cruising power, idle in-gear and idle in-neutral. PM was reduced by approximately 60 percent at high power but increased somewhat at idle. NOx was only slightly reduced at high power. There were no operational implications resulting from lower maximum power. (MARAD, 2003)

Container Ship *APL Singapore*

In spring 2007, an on-demand water/fuel emulsion system was installed on the *APL Singapore* container ship using funding from the Carl Moyer Program and in partnership with Santa Barbara County Air Pollution Control District (SBCAPCD), the Port of Los Angeles, Port of Long Beach, Ventura County APCD, and the San Luis Obispo APCD. (APL, 2007)

In September 2007, the water/fuel emulsification of 10 percent water was used in the main engine on a voyage from Hong Kong to Los Angeles with no adverse effects to the engine. There mixture was increased to 22 percent water on the subsequent trip from Los Angeles to Oakland. University of California Riverside, CE-CERT was responsible for baseline emissions testing and will perform post-retrofit emissions testing in October 2007. (APL, 2007b)

Humid Air Injection

SCX Ferries

SCX Ferries, Inc and MARAD tested the emission reduction potential of an air humidification system on a hydrofoil ferry, WaveRider, in San Diego, California. The ferry is powered by four high-speed Detroit Diesel 12V92 engines, each rated at 1050 hp at 2300 rpm, driving two water jets. They installed a water injection (fumigation) system to reduce NOx by reducing peak combustion temperatures. The system was able to reduce NOx by about 16 percent. (MARAD, 2003)

Shore-Based After-Treatment

Union Pacific Railyard, Roseville, CA/Port of Long Beach Bulk Terminal

The Advanced Cleanup Technologies, Inc. (ACTI) emissions after-treatment system was tested on a locomotive engine at the Roseville, CA rail yard in the summer of 2007. Emissions testing data is available. The same system is scheduled to be transported and fitted to a dock-side crane for testing on at a bulk ship terminal at the Port of Long Beach in the late 2007. (ACTI, 2006)

Portable Distributed Generation

Container Ship *APL China*

In July 2007, Wittmar Engineering and Construction, Inc. (Wittmar), with financial support from the Port of Oakland, the Bay Area Air Quality Management District (BAAQMD) and Pacific Gas & Electric (PG&E), conducted a proof-of-concept test of its portable distributed generation system on the 5,100-TEU *APL China* container ship at the Port of Oakland. The liquefied natural gas (LNG) powered generator supplemented one of the ships auxiliary engines and provided partial power to the ship through the existing bow thruster transformer for an 18-hour test period. Another proof-of-concept test is scheduled for late 2007 at the Port of Richmond. (APL, 2007a)

Alternative Diesel Fuels

Royal Caribbean Cruise Lines

In April 2007 Royal Caribbean Cruises, Ltd. began to use biodiesel in its ships with gas turbines, (Royal, 2006) and in August 2007 entered into a 5-year contract with a biodiesel producer to purchase a minimum of 15 million gallons of B100 fuel in 2007 and a minimum of 18 million gallons each year thereafter. (GreenCar, 2007)

Hybrid Systems

Foss Tugboat

The Foss Tug Company of Seattle, Washington recently “laid keel” on a Dolphin class hybrid tugboat. The tugboat will be a stern drive vessel used primarily for harbor assist services. The tugboat’s electric drive units will be powered by batteries coupled with diesel-fueled generators. The vessel’s engine room will be modified to accommodate two 670 horsepower battery packs and two 335-horsepower generators. Although the main engines will have lower horsepower than those found in the existing Dolphin class tugboats (5000 hp), the total horsepower of the hybrid tugboat will be equal to that of the existing Dolphin class tugboats.

Foss anticipates a number of benefits from the use of hybrid technology. These benefits include over a 40 percent reduction in emissions of PM and NOx, lower fuel consumption, and a reduction in the noise associated with the operation of the vessel. It is anticipated that the vessel will begin operations in 2008. (Foss 2007)

Fuel Cells

There have been some limited applications of fuel cell technologies on marine vessels. Fuel cells on marine vessels have operated for several years as an auxiliary power source. In the summer of 2002, adventurer Kenichi Horie sailed *Malt's Mermaid III* across the Pacific Ocean and derived on-board electricity from a 30-watt direct methanol fuel cell made by Yuasa. In November 2002, a 300 watt fuel cell provided auxiliary power for the *Branec III* in the Route du Rhum yacht race across the Atlantic Ocean from France to Mexico. (Cropper, 2004)

In October 2003, MTU Friedrichshafen and Ballard Power Systems built a 12 meter yacht propelled by a 20 kilowatt (kW) battery/fuel cell system. The compressed hydrogen fuelled yacht has a range of 225 kilometers (km) at 6 kilometers per hour (km/hr) or 25 km at 12 km/hr. (Cropper, 2004)

Also in 2003, a 30-foot, 22 passenger, 6 kW Anuvu fuel cell-powered Duffy Electric Boat, Inc.'s DH30 water taxi was test run in Newport Harbor. The fuel cell extended the operating time of the 15 kW electric motor launch by 6 hours at about 5.5 miles per hour. Aqueous sodium borohydrate (15 percent by weight) was used to generate saturated hydrogen, which does not degrade the proton exchange membrane. The byproducts are water and borate, which is returned to the manufacturer to be reprocessed to sodium borohydrate. The sodium borohydrate was manufactured by a pharmaceutical company and was expensive. The project was not economically viable, but it demonstrated a fuel cell boat could function. (Seaworthy, 2003; CCDoTT, 2003; Seaworthy, 2006)

The San Francisco Bay Area Water Transit Authority (WTA) has plans to build a vessel with a fuel cell-powered auxiliary engine as one element of an Eco-Friendly Power System. That vessel is still in the planning stages. (WTA, 2003)

REFERENCES:

Acker, G. Jr., et al. "Experience Using LNG as a Marine Engine Fuel." *Marine Technology Society Journal*. Vol. 23, No. 2, 33-39; 1989. (Acker, 1989)

Advanced Cleanup Technologies, Inc. *ACTI When Experience Counts*; Informational Brochure 2006. (ACTI, 2006)

Alimchandani, Jai K.; A.P. Moeller – Maersk Group; Regulatory Affairs Technical Organization. "Maersk Pilot Fuel Switch Initiative". July 26, 2007. http://www.arb.ca.gov/ports/marinevess/presentations/072407/072407maepres.pdf (Maersk, 2007)

Allansson, et al. *European Experience of High Mileage Durability of Continuously Regenerating Diesel Particulate Filter Technology*; SAE Technical Paper Series, 2000-01-0480. March 2000. (Allansson, 2000)

American Presidents Line Maritime Ltd. "APL announces breakthrough plan to reduce emissions" Press Release. June 13, 2007. (APL, 2007a)

American Presidents Line Maritime Ltd. *Draft Emissions Testing Protocol: In-Use Emissions Testing of an Ocean-going Vessel Retrofitted with Emissions Control Technologies (2006/2007) APL-Singapore Container Ship*; May 01, 2007. (APL, 2007)

Baylink Ferry. SCR Project-M/V Solano, June 30, 2007. (Baylink, 2007)

Bromberg, L., et al. "Hydrogen generation from plasmatron reformers: A promising technology for NOx adsorber regeneration and other automotive applications." *Diesel Engine Emission Reduction Workshop.* Newport, RI Aug 24-28, 2003. (Bromberg, 2003)

California Air Resources Board. *Staff Report: Initial Statement of Reasons Proposed Regulation for Verification Procedure for In-Use Strategies to Control Emissions from Diesel Engines, Appendix B, Diesel Emission Control Technologies*; May 2002. (ARB, 2002)

Center for the Commercial Deployment of Transportation Technologies, California State University, Long Beach Foundation. "On Demand Hydrogen Generating System: Phase II—System Demonstration." September 30, 2003. ftp://www.foundation.csulb.edu/CCDoTT/Deliverables/2002/task%202.25/task_2.25_6_FY02.pdf (CCDoTT, 2003)

Cropper, Mark. "Fuel cells in ocean-going yachts." *Fuel Cell Today.* March 5, 2004. http://me.queensu.ca/courses/MECH430/Assets/Files/General%20Interest/Fuel%20Cells%20In%20Yachts%20March%202004.pdf (Cropper, 2004)

DieselNet. *Technology Guide: Diesel Oxidation Catalyst*; 2002. http://www.dieselnet.com/tech/cat_doc.html (DieselNet, 2002)

DieselNet. http://dieselnet.com/tech/engine_adv.html (DieselNet, 2002a)

DieselNet. *Engine Design for Low Emissions: Water in Diesel* Combustion; DieselNet Technology Guide. September 29, 2006. http://www.dieselnet.com/tech/engine_water.html; (DieselNet, 2006)

DieselNet. *Diesel Emission Control*; DieselNet Technology Guide. September 29, 2006. http://www.dieselnet.com/tech/engine_control.html (DieselNet, 2006a)

"Easier on the Marine Environment." biodiesel.org http://www.biodiesel.org/markets/mar/ Date accessed: November 1, 2006. (Biodiesel.org, 2006)

Foss Maritime Company. "World's First True Hybrid Tug to be Built by Foss Maritime." Press Release. March 7, 2007. http://www.foss.com/press/Press_Release_030207.html (Foss 2007)

Frank Angelacci, American Presidents Line Maritime Ltd. Personal communication. September 10, 2007. (APL, 2007b)

"Fuel Cell Boat Tested in Newport, California Harbor; Millennium Cell, Seaworthy, Duffy Boat and Anuvu Demonstration Takes to the Water." *Business Wire*. August 21, 2003. (Seaworthy, 2003)

Green Car Congress, "Royal Caribbean Cruises Signs Long-Term Biodiesel Contract with Imperium Renewables." Press Release. August 7, 2007. http://www.greencarcongress.com/2007/08/royal-caribbean.html (GreenCar, 2007)

Holland America Line. *Holland America Line - MS Zaandam Sea Water Scrubber Technology Demonstration Project Environmental Impact Assessment (EIA) Plan*; August 10, 2007. (Holland, 2007)

International Maritime Organization, Marine Environment Protection Committee, 55th Session. *Prevention of Air Pollution From Ships; Washwater Criteria for Exhaust Gas Cleaning Systems – SOx (EGCS-SOx) Units Submitted by the United Kindom*; July 7, 2006. (IMO, 2006)

Joseph Calavita, California Air Resources Board. Personal communication. October 5-6, 2006. (ARB, 2006)

Kendall, Tom; Johnson Matthey. *Platinum 2002*; May 2002. http://www.platinum.matthey.com/publications/1051543656.html (Kendall, 2002/2003)

Kendall, Tom; Johnson Matthey. *Platinum 2003*; May 2003. http://www.platinum.matthey.com/publications/1059138410.html (Kendall, 2002/2003)

Khair, Magdi, Dale L. McKinnon *Performance Evaluation of Advanced Emission Control Technologies for Diesel Heavy-Duty Engines,* SAE 1999-01-3564; 1999. (Khair, 1999)

Lee Arkus, Interstate Diesel – McBee. Personal Communication. October 20, 2006. (Interstate Diesel, 2006)

M.J. Bradley and Associates. *Staten Island Ferry: Alice Austen Vessel SCR Demonstration Project Final Report*; August 2006. (Bradley, 2006)

Martin Robbins, Baylink Ferry. Personal communication. October 24, 2006. (Baylink, 2006)

Marty Toyen. Seaworthy Systems. Personal communication. October 27, 2006. (Seaworthy, 2006)

Munters Europe AB. *DEC SCR Converter System*. April 26, 2007. (Munters, 2007)

Royal Caribbean Cruises Ltd. "Royal Caribbean Reports Second Quarter 2006 Earnings." Press Release. July 27, 2006. (Royal, 2006)

San Francisco Bay Area Water Transit Authority. "Congress Floats Fuel Cell Boat with $2.5 Million." Press Release. February 20, 2003. http://www.watertransit.org/pubs/FuelCellBoat.pdf (WTA, 2003)

San Francisco Bay Area Water Transit Authority. "The SF Bay Area Water Transit Authority is Building Boats." Press Release. May 9, 2006. http://www.watertransit.org/pressreleases/pressRelease050906.pdf (WTA, 2006)

Thompson, Gregory J., et al. "Evaluation of Exhaust Emissions from Elizabeth River Ferries: Final Report." Department of Mechanical and Aerospace Engineering, West Virginia University. July 2002. http://cafee.wvu.edu/Assets/Documents/Report%20-%20Evaluation%20of%20Exhaust%20Emissions%20from%20Elizabeth%20River%20Ferries.pdf (Thompson, 2002)

Tina Stotz, Holland America Line, inc. Personal communication. September 14, 2007. (Holland, 2007a)

U.S. Department of Transportation Maritime Administration Office of Shipbuilding and Marine Technology. *Energy Technologies. Newsletter No. 04*; Winter 2003-2004.

http://www.marad.dot.gov/nmrec/energy_technologies/images/ETNo4Winter0304.htm Date accessed: August 9, 2006. (MARAD, 2003)

U.S. Environmental Protection Agency (EPA). *Air Pollution Control Technology Fact Sheet: Flue Gas Desulfurization (FGD) – Wet, Spray, Dry, and Dry Scrubbers*. EPA-452/F-03-034. July 7, 2003. http://www.epa.gov/ttn/catc/dir1/ffdg.pdf(EPA, 2003)

U.S. Environmental Protection Agency (EPA). *Final Regulatory Analysis: Control of Emissions from Nonroad Diesel Engines Chapter 4*. EPA420-R-04-007. May 2004. (EPA, 2004)

von Wedel, Randall. Technical Handbook for Marine Biodiesel in Recreational Boats. Second Ed. April 22, 1999. www.cytoculture.com/Biodiesel%20Handbook.htm (von Wedel, 1999)

Wilcox, LT R. "Risk-based Technology Methodology for the Safety Assessment of Marine Compressed Natural Gas Fuel Systems." *International Cooperation on Marine Engineering Systems/The Society of Naval Architects and Marine Engineers*. New York Metropolitan Section Symposium; May 22-23, 2000. http://homeport.uscg.mil/cgi-bin/st/portal/uscg_docs/MyCG/Editorial/20060804/01-00.pdf?id=c5c49be78f122ae2d6558aed8a54d5b80dcf28f9 (Wilcox, 2000)

Wittmar Engineering & Construction, Inc. *American President Line; DFMV Cold Ironing™ Presentation.* September 6, 2006. (Wittmar, 2006)